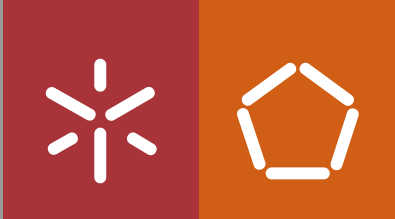


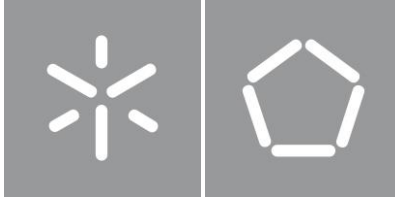


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Construction Waste Management Model for
Contractors Using Lean and BIM Tools

Universidade do Minho
Escola de Engenharia





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Philosophy Doctorate Thesis

Civil Engineering

Work conducted under supervision of:

Professor Doctor José Manuel Cardoso Teixeira

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism, any form of undue use of information, or falsifying results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

The research is not directed towards any specific demographic warranting distinctive ethical attention. Given its focus on professionals such as contractors, architects, trades, and lean practitioners, the primary ethical concerns centre around safeguarding the privacy, confidentiality, and anonymity of participating companies, subjects, and questionnaire respondents. The literature review upheld meticulous citation and electronic management for all scholarly sources. Additionally, the sources of data were duly acknowledged during the dissemination of research outcomes to enhance the reliability of the data.

Resumo

Os resíduos de construção continuam a ser um desafio significativo para o sector, dificultando a produtividade e desencorajando a inovação. Vários relatórios descrevem os seus impactos adversos, tais como o obstáculo ao desenvolvimento da sustentabilidade ambiental, económica e social. Os académicos, os reguladores e as sociedades profissionais apelam continuamente a uma indústria sem resíduos. No entanto, a concretização deste objetivo ambicioso continua a ser contrária à situação atual, uma vez que a regulamentação, as políticas e as práticas existentes ainda têm origem em processos tradicionais de gestão da construção que se centram no tratamento dos resíduos tal como são, no final, em vez de começarem na fonte de produção de resíduos. Esta tese centra-se na exploração do problema generalizado do desperdício de Making-Do (MD) em projectos de construção, com a utilização dos princípios da Lean (LC), em particular o Last Planner System (LPS) reforçado pela Modelação da Informação da Construção (BIM), para desenvolver estratégias de mitigação do MD. Os resíduos de MD gerados pela realização de tarefas de construção sem os pré-requisitos necessários causam ineficiência, aumento de custos e redução da qualidade num projeto. Inicialmente, a revisão sistemática da literatura identificou um conhecimento limitado dos resíduos de MD e a falta de uma abordagem integrada para os mitigar. Esta investigação analisa então os factores subjacentes aos resíduos de MD, os elementos dos resíduos de MD e os seus efeitos, sintetizando os resultados da revisão da literatura e dos questionários estruturados. Com base nesta avaliação, as causas potenciais do desperdício de MD podem estar relacionadas com o planeamento, a comunicação e o conhecimento entre os trabalhadores. Com base nestes resultados, a investigação criou um novo Modelo Dinâmico de Sistema - o Modelo Dinâmico para a Mitigação do Making-Do (D3M) para modelar e avaliar os efeitos do LPS e do BIM na redução dos resíduos de MD. O D3M combina os resultados dos inquéritos por questionário e estudos de caso de projectos de condomínios de vários andares, em que os aspectos técnicos e sociais são quantificados para fornecer tendências gerais na geração e propagação de resíduos de MD. O modelo permite testar vários cenários de implementação do LPS-BIM em termos da sua eficácia na redução dos resíduos de MD e na melhoria dos resultados do projeto. Os resultados destacam a importância do planeamento colaborativo e da análise das restrições, da partilha transparente de informações através do BIM e de uma cultura que dê prioridade à prevenção e resolução dos resíduos de MD. Assim, esta investigação oferece um modelo de aplicação e uma ferramenta de simulação baseada em modelos (D3M) para a prática de integração LPS-BIM para a minimização dos resíduos de MD, a fim de beneficiar os profissionais e os investigadores no aumento das possibilidades de sucesso nos projectos de construção.

Palavras-chave: Construção Lean (LC); Modelação de Informação de Construção (BIM); Resíduos de Construção; Modelagem Dinâmica de Sistemas (SDM); Resíduos de improvisação.

Abstract

Construction waste remains a significant challenge for the industry, hindering productivity and discouraging innovation. Various reports outline its adverse impacts, such as hindering environmental, economic, and social sustainability development. Academics, regulators and professional societies continuously call for a zero-waste industry. However, achieving this ambitious objective remains contrary to the actual situation, with the existing regulations, policies and practices still originating from traditional construction management processes that focus on treating wastes as they are, in the end, instead of starting from the source of waste generation. This thesis focuses on the exploration of the pervasive problem of Making-Do (MD) waste in construction projects, with the use of Lean Construction (LC) principles, particularly the Last Planner System (LPS) enhanced by Building Information Modelling (BIM), to develop mitigation strategies for MD. MD waste generated by undertaking construction tasks without the required prerequisites causes inefficiency, increased cost and reduced quality within a project. Initially, the systematic literature review identified limited knowledge of MD waste and the lack of an integrated approach for mitigating it. This research then reviews the factors behind MD waste, elements of MD waste, and its effects by synthesizing the outcomes of literature review and structured questionnaires. Based on this evaluation, potential causes of MD waste can pertain to planning, communication, and knowledge among workers. Based on these results, the research has created a new System Dynamic Model - the Dynamic Model for Making-Do Mitigation (D3M) to model and assess the effects of LPS and BIM on MD waste reduction. D3M combines results from the questionnaire surveys and case studies of multistorey condominium projects where technical and social aspects are quantified to provide general trends in generating and propagating MD waste. The model enables various LPS-BIM implementation scenarios to be tested in terms of their effectiveness in reducing MD waste and enhancing project outcomes. Findings highlight the importance of collaborative planning and constraint analysis, transparent information sharing through BIM, and a culture prioritising MD waste prevention and resolution. Thus, this research offers an application model and a model-based simulation tool (D3M), to the LPS-BIM integration practice for MD waste minimisation to benefit practitioners and researchers in enhancing the chances of success in construction projects.

Keywords: Lean Construction (LC); Building Information Modelling (BIM); Construction Waste; System Dynamic Modelling (SDM); Making-Do waste.

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LIST OF ABBREVIATIONS

2D-CAD Two-Dimension Computerised-Aided-Design	33
4D 3D BIM model elements associated with time	38
AECO Architecture, Engineering, Construction and Operations	33
AHP Analytical Hierarchy Process	75
AON Activities On Nodes	27
AVE Average Variance Extracted	121
BIM Building Information Modelling	33
CBA Choosing-By-Advantage	24
CCC Construction Consolidation Centers	22
CDW Construction and Demolition Waste	2
CFI Comparative Fit Index	119
CLD Casual Loop Diagram	98
CPM Critical Path Method	37
CR Composite Reliability	121
CSC The Construction Supply Chain	21
FL Flow Line	32
GIS Geographic Information System	39
HTMT Heterotrait-Monotrait	122
ICT Information and Communication Technology	94
IFOA Integrated Forms of Agreements	25
IGLC International Group of Lean Construction	41
IPD Integrated Project Delivery	25
ISO International Organization for Standardisation	33

JIT Just-In-Time	22
KMO Kaiser-Meyer-Olkin	116
KPIs key performance indicators	73
LBMS Location-Based Management Systems	29
LBS Location-Based-Structure	30
LC Lean Construction	37
LDM Lean Design Management	16
LPC Lean Planning and Control	16
LRA Linear Regression Analysis	60
LSCM Lean Supply Chain Management	16
NaN Not a Number	182
NFC Near-Field Communication	39
NVA Non-Value-Added	23
PERT Program Evaluation and Review Technique	2
PPC Per cent Plan Complete	98
PPC Plan Percent Complete	28
QT Queuing Time	23
RCA Root Cause Analysis	25
RFI Request for Information	40
RFID Radio Frequency Identification	38
RMSEA Root Mean Square Residual	119
SBD Set-Based-Design	24
SRMR Standardized Root Mean Square Residual	119
STELLA Experimental Learning Laboratory with Animation	75
TFV Transformation-Flow-Value	18

TLI Tucker-Lewis Index	119
TPS Toyota Production System	17
TT Takt Time	23
TTP Takt Time Planning	32
TVD Target-Value-Design	24
WBS Work Breakdown Structure	30
WIP Work-In-Progress	23
WMP Material Waste Management Plan	25
WWP Weekly Work Planning	27

1. Introduction

This chapter presents a general overview of the thesis, opening with the main objectives of the research motivation. A brief description of the research methodology includes the main theoretical and methodological approaches to achieve the thesis objectives. The thesis structure is outlined, with short descriptions for each chapter illustrated.

1.1. Motivation

The construction industry is a significant waste generator for many academic, regulatory, policymaker, and professional agencies worldwide. This waste is exacerbated by social, economic, managerial and technical factors caused by a push mindset in decision-making and reactive problem-solving rooted in traditional construction management theories and practices, primarily the derived policies used during planning and control. Much research has shown enormous amounts of waste in different construction flows. The amount of material waste - construction and demolition waste (CDW) - in the European Union (EU) represents one-third (38.49%) of the total reported waste in the region. Various CDW management initiatives exist, including waste management directives, circular economy, and design-out-waste, which form constant pressure for better efficient resource consumption across the whole supply chain. According to a meta-analysis of production research (Horman & Kenley, 2005), 49.6% of project time is spent on non-value-added activities in construction. A Swedish study found that only 15% to 20% of working time is spent on value-added activities (Jongeling & Olofsson, 2007).

Most of the existing waste management strategies focus on end-of-pipe treatment (Osmani et al., 2008), therefore missing opportunistic potentials in addressing waste at root causes by investigating non-value-added (NVA) waste (Viana et al., 2012). Production management is directly related to the successful completion of projects on time and within the budget and is linked to the development of sustainability (Nahmens & Ikuma, 2012). According to the lean philosophy, waste is a central concept known as a kicking point for improvement in the Toyota Production System (TPS) (Satoshi Hino, 2005).

Nevertheless, it is an area that remains managed by *ad-hoc* decisions and is dependent on manual and traditional processes (Satoshi Hino, 2005). A plethora of research has reported poor production management due to the high ratio of NVA across the construction supply chain (Formoso et al., 2002; B. T. Kalsaas, 2010; Sacks, Korb, et al., 2018). The consensus criticised the traditional planning and control methods and described them as the source of fragmentation between process and product design, which causes weak communication and feedback loops to plans (Ballard, 2000; Bortolini et al., 2019; Sacks & Goldin, 2007). Koskela (2017) stated that construction management abstracted production and waste management concepts from its theories and methods, which, in turn, caused general contractors and project management to decline their efficiency in day-to-day practices.

Among various types of waste, Making-Do practice is a core production waste that entails in executing planned activities without their necessary inputs (materials, workers, documents, information

1. Introduction

models, and among others). This waste is considered as significant non-physical waste that persists across the whole construction supply chain (Fireman & Saurin, 2020; Formoso et al., 2020; Karaz & Teixeira, 2023b; Koskela, 2004), however, while existing research highlighting the causes and consequences of MD waste, it lacks a comprehensive framework for identifying, mitigating, and eliminating it. Moreover, production planners and trade teams require practical strategies and tools to detect, estimate, and eliminate MD waste from construction processes

Considering planning and control methods in the construction. The Critical Path Method (CPM) and PERT are most common methods in the current construction management practice. CPM and PERT are activity-based planning methods that have been criticized due their impracticality in workflow and resource management, which overwhelm stakeholders with long lead times and minimum level of detailing for the construction schedules, and lack control mechanisms at short-term intervals (Dave, 2013; Fayez et al., 2003; Jaafari, 1984; Olivieri et al., 2018; Prascevic & Prascevic, 2017). This lack of detailed short-term planning and control mechanisms can lead to situations where tasks are initiated without necessary resources readily available, resulting in MD waste.

Traditional approaches often create a disconnection between process design and product design (Sacks et al, 2010). This fragmentation hinders communication and feedback loops, leading to inefficiencies and increased likelihood of MD waste. When processes are not designed to seamlessly support the creation of the intended product, there's a higher chance of encountering unforeseen issues and resorting to making-do to overcome them. Traditional methods typically follow a top-down approach, with limited involvement of downstream trades in upstream decision-making (Ballard,2000). This lack of collaboration and early engagement can result in plans that are not well-suited for actual site conditions or the expertise of those executing the tasks, increasing the potential for MD situations. Traditional planning methods can be inflexible to changes and unforeseen circumstances. When unexpected issues arise, teams may resort to making-do to adapt to the situation rather than revisiting the original plan.

The Last Planner System (LPS) has been recommended to complement the gaps caused by the sole use of CPM for production planning and control. LPS as a socio-technical system to increase planning details with successive levels of planning details and shield downstream from upstream variability using constraints analysis (Ballard, 2000, 2020). The parallel growth of Lean Construction and Building Information Modelling (BIM) became *de facto* in modern project management and digital construction

1. Introduction

advancement, arising from the positive interactions between both concepts towards waste elimination and value generation (Sacks, Koskela, et al., 2010). This integration is envisaged as a basis for production planning and control, which supports process and product integration, engages downstream in upstream decisions, and increases the level of planning at process and operational levels (Dave & Sacks, 2020). Regardless of the importance of BIM in production planning and control, most current BIM systems provide activity-based planning represented by 4D planning functionality, which is insufficient for production planning and control purposes (Ratajczak et al., 2019). A few authors have recently developed advanced production and control models accounting for lean construction principles and BIM functionalities (Dave & Sacks, 2020; Heigermoser et al., 2019; Schimanski et al., 2020).

Unfortunately, the actual behaviour of the construction production systems is exacerbated by uncertainty and complexity. Similarly, the construction waste inherits the properties of the construction production system. It is challenging to provide holistic models of construction waste; the current solutions are designed based on operational information from specific projects or processes and on *ad hoc* decisions from professional experience. The lack of holistic construction elimination models often leads to quality defects, cost, and schedule overruns.

The influence of planning and control using lean construction and BIM on the behaviour of MD waste elimination is essential and should be studied. Furthermore, clear and straightforward guidelines are necessary for adequate production planning assessment and proactive control, which should be readily available among owners, contractors, and subcontractors. Moreover, many existing projects are still managed traditionally without adequate control (i.e. real-time resource tracking, short-term planning and adjustment mechanisms, structured feedback loops and learning), which are still reluctant to generate high levels of different types of waste.

1.2. Objectives

As previously exposed, the amount and variety of waste in the construction industry are incredibly high, complex, interrelated, and uncertain. However, many proposed frameworks do not consider the role of planning and control in managing construction waste at source. Therefore, questions about production design, preplanning, scheduling and control, the interaction of stakeholders with production information, and their operational effects need to be explored. Understanding the underlying structure of making-do (MD) waste in construction project environments, especially when planning and controlling for production, is essential to achieving the ideal "zero waste" status. Accordingly, a holistic system called D3M

1. Introduction

(Dynamic Model for Making-Do Mitigation) will be explored and developed to fulfill the following objectives.

- Develop a holistic waste elimination knowledge using lean construction theories, principles, methods, techniques, and tools - a systematic literature review is applied for this purpose,
- Explore the casual structure of MD generation and mitigation, the current views of Last Planner System (LPS), and BIM professionals are considered to map the relationships.
- Provide a simulation based on system dynamics capable of studying the influence of the last planner system and building information modelling on making-do waste specifically, as well as the overall production waste and overall project performance system.
- Develop a lean-based policy for MD waste assessment of the construction production system.

1.3. Thesis Outline

The research work conducted in this thesis is organized into eight chapters. The overall research framework is presented in Figure 1-1, and it incorporates three main tasks: (i) literature review, (ii) explore the dynamic relations of MD waste within the production subsystems, and (iii) development of dynamic decision support tool for MD mitigation that applies the Last Planner System and Building Information Modelling (BIM). The current chapter (Chapter 1) contains research motivation, objectives, and a brief description of the methods utilised to achieve the research objectives. It also outlines the structure of the thesis by describing each chapter.

Chapter 2 presents a systematic literature review (SLR) study on 54 relevant documents. SLR aimed to (i) understand 'waste' and 'waste elimination' concepts through LC perspectives and (ii) review factors of LC-BIM for waste elimination. According to thematic analysis applied to the existing LC-BIM approaches, particularly the Last Planner System (LPS) and Location Based Management (LBMS) approaches. The SLR shows that the current literature lacks the concept of waste elimination in the number and content of publications. The SLR highlights some recommendations for theoretical and empirical developments that will be utilised in the following chapters.

Chapter 3 justifies the choice of research methodology, data collection, and analysis methods; it formulates the theoretical framework, introduces System Dynamics Modelling (SDM), and finally reviews the integrated approach of both methods.

1. Introduction

Chapter 4 applies a qualitative study to explore the different definitions of MD and the strategies that limit MD waste propagation. The Casual Loop Diagram (CLD), given the causal structure of variables interrelated with MD generation and mitigation, the CLD utilised to determine the causality between production planning and control functions and MD waste propagation. The secondary data was collected from the literature to assemble the sub-systems of the study using Stock and Flow Diagrams (SFD). This chapter suggests new policies and strategies for eliminating MD using LPS and BIM.

Chapter 5 provides an analysis based on the combined approach of SDM from Chapter 4 and Agent-Based Modelling (ABM) to simulate the dynamics of LBMS, LPS, and BIM with the effect of social agents on waste elimination. This chapter ends with development process maps that 1) assign responsibilities between owners, contractors, and subcontractors and 2) illustrate the information flow and the procedure of LBMS, LPS, and BIM.

Chapter 6 emphasises the mathematical models that have guided the development of the dynamic model structure. A multiple-source data case study and a comprehensive questionnaire survey offer a more strategic approach to understanding the problem. The chapter uses statistical data, data collection, and simulation design features, both primary data sources. Basic analysis models such as Multiple Linear Regression Analysis (MLRA) and Structural Equation Modelling (SEM) expose complex system interconnections and relationships. The LPS-BIM framework by SEM allows for examining LPS-BIM parameters on the negative effect of MD, constraints, and waste categories. Moderation and mediation analysing mechanisms will be used to estimate the impact of LPS technical, Collaboration (COO), BIM functions, and MDK factors. However, again, CFA analysis verifies that LPS-BIM factors can mitigate MD issues, while simulation models provide evidence that the incidence of MD findings is very typical in the case of planning and quality control, mandating a high pace of response.

Often, the question of task execution without constraint screening and maladapted input actions is omitted in traditional planning and controlling. This behaviour leads to MD practices. Chapter 7 measures the success of LPS and BIM, which would be the key to tackling these challenges. Three main objectives are outlined: the development of SDM, including resources, work progress, productivity, locations, and budgeting elements as they relate to guarding procedures examination; additionally, the inclusion of LPS and BIM dynamic features into the model and performing simulations to gauge their efficiency the in mitigating MD is being deliberated. The causal structure is drawn by quantitative analysis, and the scheme is shown visually through an SFD, which includes the mathematical equations.

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The case study methodology will enable the model to adapt to the changes in policy structures, technological advancements, and the market landscape to further the model's validity. In conclusion, the essence of this conclusion rushes towards the suggestion that the policies with a concept of lean management may be the cure from which MD has originated and perhaps such a specific kind of approach that was not discovered.

The last chapter (Chapter 8) summarises the thesis conclusions and limitations, as well as recommends an agenda for future research that can be carried out.

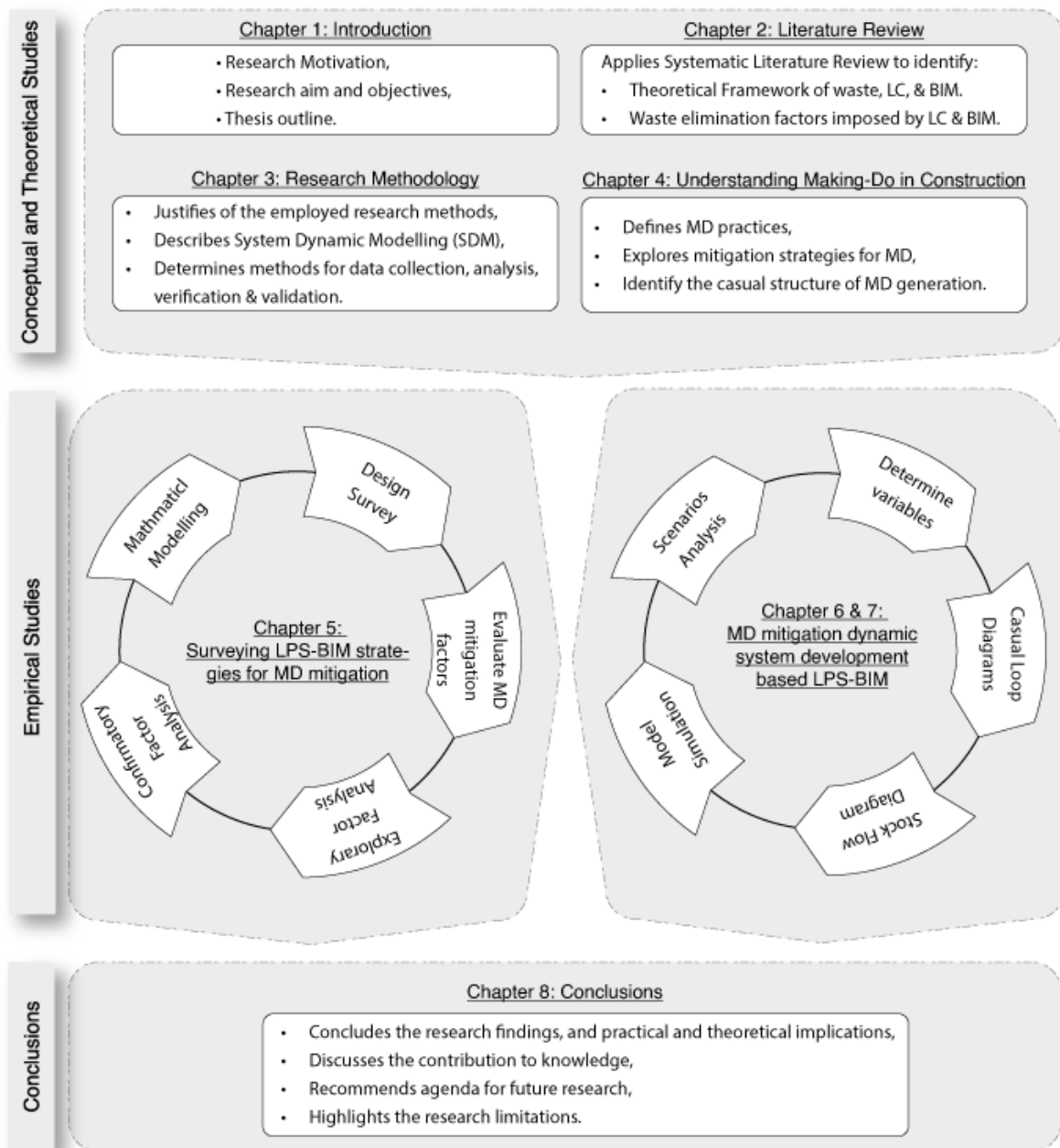


Figure 1-1: Research methodology and thesis overview

2. Literature Review

This chapter presents the state of the art of the studied topic and provides a thematic analysis for lean construction methods. Finally, it identifies the research gaps in the literature and presents a theoretical framework.

Except for some changes executed for the formatting and organisation purposes of global information in this document, this chapter integrally presents the work:

(Karaz & Teixeira, 2023b). Waste Elimination based on Lean Construction and Building Information Modelling: A Systematic Literature Review. U. Porto Journal of Engineering, 9(3), 72–90.
https://doi.org/https://doi.org/10.24840/2183-6493_009-003_001808

2.1. Introduction

Construction waste is a high-level concept behind poor productivity and low innovation levels in the industry, which is challenging to measure systematically. The plethora of reports shows the massive consequences of construction waste, which hurdles sustainability development in its three dimensions (environmental, economic, and social). Regarding materials, one-third of the global construction material is landfilled without treatment (Yuan & Shen, 2011). The second type of waste is environmental, the industry's greenhouse gas (GHG) footprint; 33% of the global GHG is released from construction and transportation projects (UN, 2017). Construction and Demolition material Waste (CDW) and GHG emissions concern many regulators, such as the European Commission to publish several directives to impose strategies for the negative environmental impact of the construction (i.e., EU waste directive (2008/98/EC), The Energy Performance of Buildings Directive (2010/31/EU) among others).

However, none of the provided directives have discussed the root causes of the emerging issues, and most of the proposed regulations and guidelines offer end-of-pipe solutions without proposing countermeasures that tackle waste at source (Osmani et al., 2008). Hence, most developed regulations deal with symptoms of waste rather than targeting how waste is produced in terms of production waste. That takes time units into the formula of waste generation. Production waste is usually called non-value added (NVA), defined as any activity that absorbs resources (e.g., time, location, material, energy, and others) without adding value to internal or external customers. According to the meta-analysis of Horman & Kenley (2005), NVA activities constitute 49.6% of the construction operations. The literature has investigated different types of NVA, including rework (Love & Li, 2000a), product defects (Josephson & Hammarlund, 1999), waiting (Sacks, 2016), transportation (Belayutham et al., 2016), intuition and intuition waste (Sarhan et al., 2017),. And the relation between production and environmental waste (Carvajal-Arango et al., 2019; Golzarpoor et al., 2017; Golzarpoor & González, 2013; Nahmens & Ikuma, 2012). This disparity in measuring and defining waste measures increases the difficulty of formulating holistic and hurdles efforts of providing general guidelines for root causes analysis (Formoso et al., 2020). Additionally, many reported types of waste are measured empirically at an operational level or professional experience, which challenges a comprehensive judgment on the nature of generated wastes and their relationships with other types.

Toyota Production System (TPS) first attempted a taxonomy for production waste, which was

2. Literature Review

supposed to be achieved by attacking overproduction and reducing inventory, operational advantages at the production level, and increasing profits at the organisational level with minimum investment (Ohno, 1988). On this basis, lean production was founded as a waste elimination-focused philosophy to generate customer value with zero waste ideally. Lean production considers waste an actionable language that brings stakeholders' attention to actual causes of inefficiency; Womack and Jones (2003) drew from a set of principles adopted in various industries, including construction. Lean Construction (LC) adopted these principles to reduce cycle time and product and process variability, enforce continuous improvement, and increase transparency (Koskela, 2000; A. Santos, 1999). In addition, other principles, including 'map for value stream,' 'establish for pull planning,' and 'structure the construction process into flows,' are also used (Koskela et al., 2002).

From a theoretical point of view, LC is founded on the Transformation-Flow-Value (TFV) theory, which states that traditional construction management sees the process as input-process-output is a counterproductive perspective because it is a black-boxed definition that hides wastes inside the process which resolves production problems after occurring. The TFV suggests adding two more concepts, Flow (F) and Value (V). That forms a new paradigm in construction projects, where F aims to break down the construction process into NVA and VA, as shown in Figure 2-1, to provide technical metrics to understand and control the construction progress and problems proactively. The V perspective adds a social dimension by encouraging the upstream to understand the downstream requirements, which should work collaboratively to reap global project optimisation instead of focusing on local optimisation.

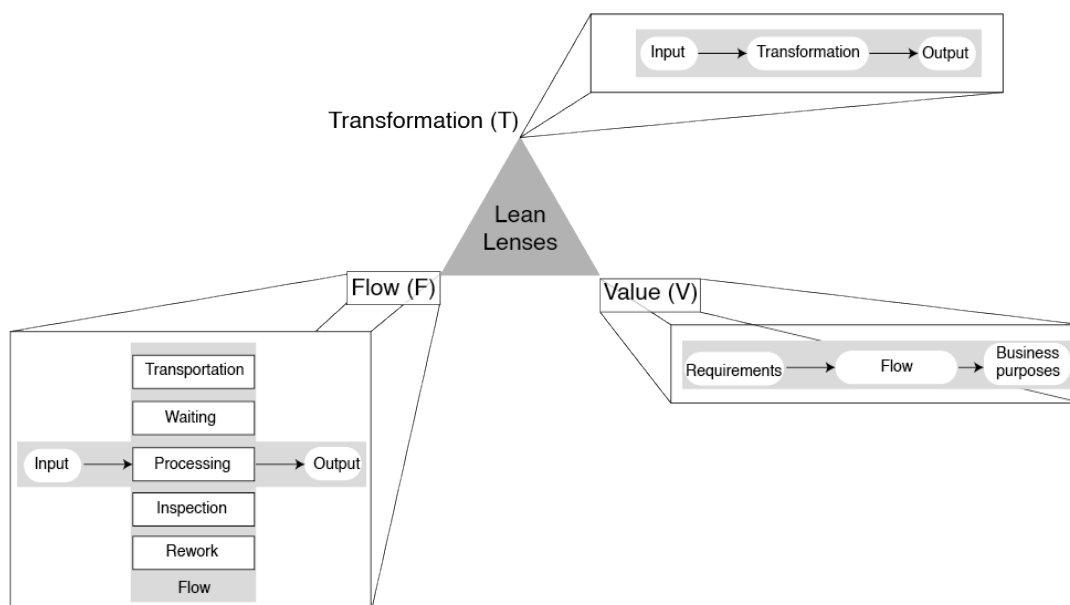


Figure 2-1 – Transformation-Flow-Value theory

2. Literature Review

In practice, lean construction cannot be applied only from the early stages until handover but also at the end-of-life/extension-of-life stages of a building (e.g., demolition, renovation, retrofitting, expansion). This application extends across the whole construction supply chain. The ideal Lean Supply Chain Management aims to deliver construction products on time, which relies on pulling information about the product and process from production signals rather than solely forecasting demand (Bortolini et al., 2019; Vrijhoef, 2020). Production signals should be pulled from reliable plans that are retrieved from LC planning and control systems (i.e., Last Planner System® (LPS) and Location-Based-Management System (LBMS)). The LPS is a context-specific and socio-technical system that aims to improve planning reliability through successive collaborative sessions to shield the downstream from upstream variability (Ballard, 2020). At the same time, LBMS is a spatial, temporal system that technically plans and structures the construction operations according to their locations (i.e., floor, zones, sections, and floors) (Kenley & Seppänen, 2010). LPS and LBMS can be used concurrently to address waste such as work-in-progress, waiting, space congestion, and overproduction (Frandsen et al., 2014). Those wastes will be discussed and removed collaboratively after acknowledging work structure, sequencing, resource allocation, and associated constraints.

Due to the intensity of the production information, labour and manual inputs for LPS and LBMS can hinder planning reliability. So, Building Information Models (BIMs) are essential to communicate real-world data streamlined from LC planning and control systems and support the decisions both systems take. According to Sacks et al. (2010), BIM functionalities are recognised as a coherent and consistent source of information that can provide up to 56 positive interactions with lean principles. A significant example of LC-BIM is the integration of LPS into the BIM 4D model, which assists in filtering trade activities according to task readiness and enables managers to track the production progress and bottlenecks using the production metrics (Sacks et al., 2010). Those metrics include construction production rate, resource consumption, flow index, Plan Percent Complete (PPC), and task maturity, which can be translated into Andon signals to bring stakeholders' attention to production wastes (Dave, 2013). The empirical research shows that LPS-BIM's effectiveness for waste elimination is partial without real-time tracking, which is improved through digital monitoring, artificial intelligence, and linked data, among other technologies (Dave & Sacks, 2020).

Additionally, LBMS can benefit from BIM workflows supporting LBMS forecasts with accurate material take-offs and location interference analysis. Moreover, LC-BIM has a positive impact on accelerating the adoption of other initiatives, including 4.0 construction, circular economy, design-out-

2. Literature Review

waste (Karaz et al., 2021), and Design for Manufacturing and Assembly (DfMA) (Gbadamosi et al., 2019). The planning and control-based LC-BIM approach holds vast waste elimination opportunities for sustainability (Saieg et al., 2018).

The objectives of this chapter are to explore lean construction approaches to conceptualise construction waste, to identify waste elimination factors presented by lean construction at various stages of the construction supply chain, and to review the relationship between Lean principles and BIM functionalities to address construction waste. The chapter utilises the systematic literature review method to achieve these objectives. The systematic review found four gaps regarding the concept of waste in construction management research as follows: i) persistent construction management theories in the current research and practice, ii) a holistic theory that explains waste propagation and its characteristics is not presented yet, iii) ambiguity in the reported data collection methods for waste, iv) variety in conceptualisation to address similar types of waste.

2.2. Systematic Review Research Questions

A plethora of research attempts to investigate the impact of LC and BIM on improving production and planning using the concepts of waste elimination and value generation. However, LPS-based and LBMS-based BIM utilisation remains parallel where models are presented while collaborative planning takes place with low automation and maturity levels. Additionally, the presented research lacks explicit definitions and measures for construction waste, which is rarely captured systematically. A comprehensive and integrative literature review is needed to understand how lean construction and BIM interact to reveal and eliminate waste systemically. Therefore, this chapter investigates these gaps by adopting the SLR methodology. The formulated SLR questions are defined as follows:

1. How does lean construction conceptualise waste?
2. What are waste elimination factors imposed by lean construction (LC)?
3. What are the factors of LC-BIM that contribute to waste elimination?

This chapter is structured as follows: Section 2.3 presents a detailed description of the systematic literature review methodology and a descriptive analysis of the publications in this field over time. Section 2.4 presents content and thematic analysis to cluster the existing research into four research themes. Section 2.5 concludes the performed analysis and discusses further development needed to

2. Literature Review

improve the current understanding and application of waste elimination in the construction industry.

2.3. Materials and Methods

Year by year, enormous research is conducted with conflicting understandings of construction waste and various interventions to tackle it. A Systematic Literature Review (SLR) is a method to understand a context-specific problem and laud the suggested interventions by the literature to address that problem by synthesising the dispersed results from evidence-based literature. An SLR should be a transparent, upgradable, transferable, and quality exclusive review Denyer & Tranfield, (2009). However, the constraints of SLR are limited to a time-consuming review methodology that requires additional resources compared to traditional methods (Mulrow, 1994; Wohlin & Claes, 2014).

The adopted SLR methodology is illustrated in Figure 2-2, which shows that SLR comprises four iterative stages: (1) planning for the review, (2) material collection, (3) data evaluation, and (4) results reporting and dissemination (Tranfield et al., 2003). During 'planning for the review,' the review question is developed in the following section as an early-stage process that conceptualises and formulates complex problems into a contextual frame (Flemming et al., 2019).

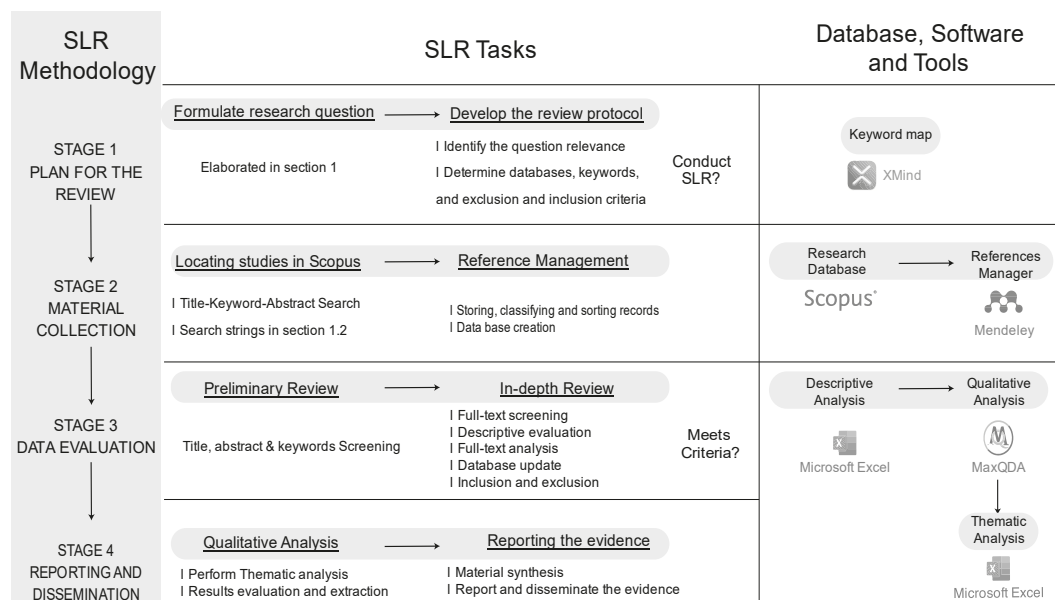


Figure 2-2– Systematic Literature Review (SLR) Methodology

The literature data were collected using the Scopus database, IGLC, and snowballing techniques during the material collection stage. Most retrieved documents are from the Scopus database that was queried by using two entries: the first query is a preliminary search string that combines only the study

2. Literature Review

keywords' lean construction' and 'BIM' and 'waste' using the 'AND' operator; the second query was formulated using the 'AND 'OR' operators to extend the search range and also included the Title-Abstract-Keywords using the streamlined keywords in the tree map (Figure 2-3). The keywords used were adapted from (Tezel et al., 2020; Viana et al., 2012). At the same time, the snowballing technique followed the procedure suggested by (Wohlin & Claes, 2014).

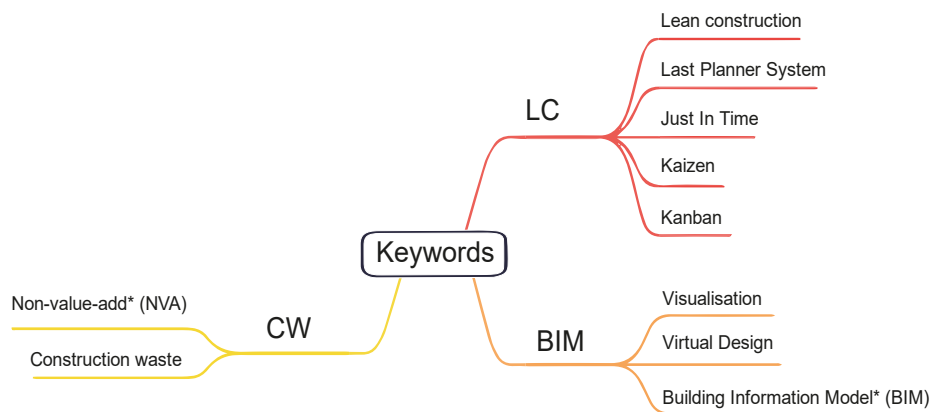
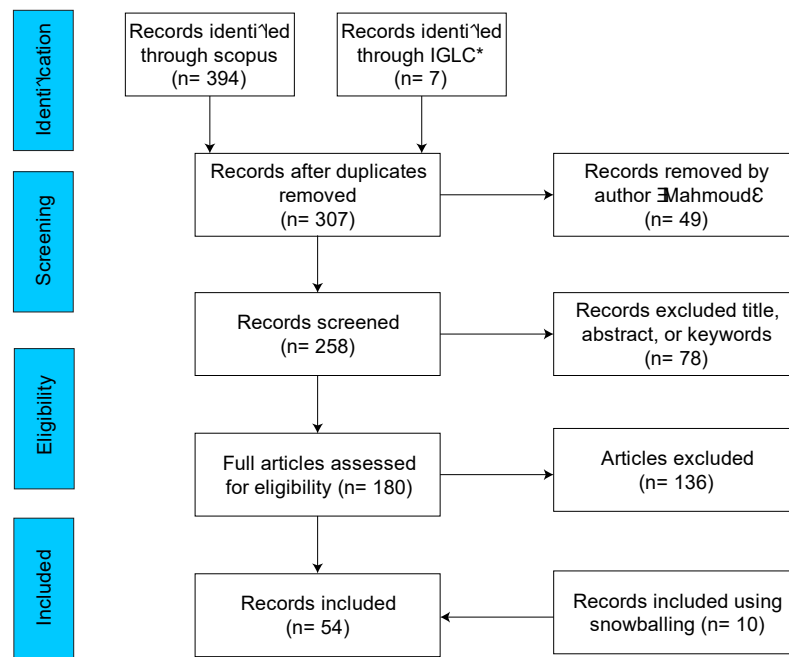


Figure 2-3 – A mind map of streamlined keywords

After querying the selected databases, the number of included documents for a preliminary analysis was (411) records, as illustrated in Figure 2-4. The inclusion/exclusion criteria are summarised in Table 1 to filter the number of documents included. The requirements are applied for publishing year, researched concepts, research domains, and language. After using the specified including/exclusion criteria in Table 2-1, the number of research documents was narrowed to (190) after screening Titles and Abstracts. In contrast, (136) documents were excluded after full-text analysis, so the number of relevant documents (54) is to be analysed in this paper.

2. Literature Review



* IGLC: Proceedings of International Group of Lean Construction

Figure 2-4 – Prisma diagram applied to researched documents

Table 2-1: Inclusion and exclusion logic used to filter research documents

Criteria	Inclusion	Exclusion
Publishing Year	1999-2022	Earlier than 1999 and later than 2022.
Discussed Topics	Combine LC and waste concepts, OR LC, BIM, and waste.	Studies are on only one concept: studies on BIM and waste only.
Research Domain	Construction management domain with a focus on LC concepts.	Other domains than LC management.
Publication Language	The English language only.	Other than English.

2.4. Data Evaluation

This section employs descriptive analysis to provide a broad overview of waste elimination development through LC and LC-BIM over time. Firstly, the study aimed to depict how the topic quantitatively developed over time. Figure 2-5 illustrates that the number of waste elimination papers has risen. From

2. Literature Review

early 1992 until the first quarter of 2022, most literature recognised waste elimination as a central concept of LC. In 2008, the impact of LC-BIM on waste elimination emerged (Eastman et al., 2008).

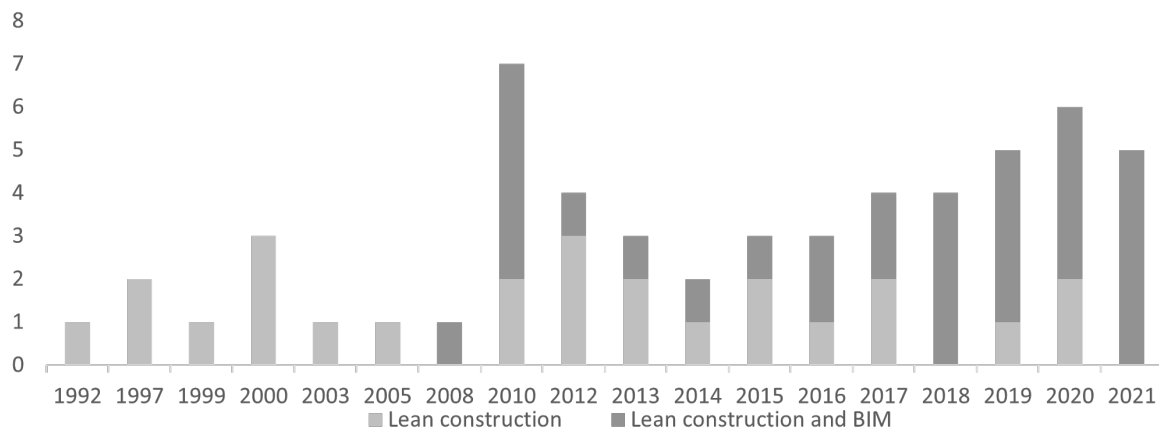


Figure 2-5– The number of documents contributed to waste elimination based on LC and LC-BIM from 1992 to 2022

The proportion of relevant documents that used the LC-BIM approach is 53.70%, while 46.30% of selected records utilised LC theory and methods. Figure 2-6 presents an analysis of the objective of waste elimination research, which was classified into (i) conceptual, (ii) literature review, and (iii) empirical.

The first class includes papers on theory and predominantly on historical and conceptual analysis of construction waste. The second class represents literature review papers that develop integrative solutions based on secondary data from evidence-based literature. Empirical papers are those aimed to provide applications or adaptations for LC and LC-BIM solutions in a specific context of the construction supply chain, for example, (i) reporting problems and prescribing a solution for that problem, (ii) implementation of LC principles, methods, tools, and techniques, (iii) define the requirements for waste elimination solutions-based LC-BIM (iv) evaluation of LC and LC-BIM solutions, (v) use of IT artefacts; among others.

2. Literature Review

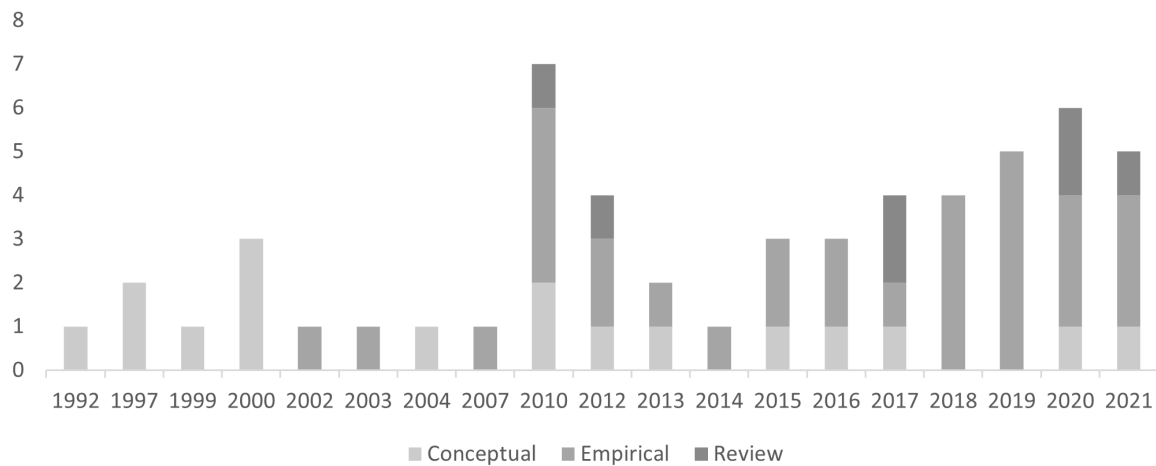


Figure 2-6– A distribution of the research methods from 1992-2021

The analysis demonstrates that the focus of the literature has been mainly empirical rather than theoretical and literature review, as shown in Figure 2-7. Additionally, this highlights that theory is not evolving at the same rate as practical implementation, and there are limited successful examples, hence weak support for waste elimination in LC-BIM implementation. The analysis in Figure 2-7 classified the empirical research into four functional areas of the construction supply chain management, namely (i) Lean Supply Chain Management (LSCM), (ii) Value stream Mapping, (iii) Lean design management (LDM) and (iv) Lean planning and control (LPC). That shows that little empirical research was conducted on post-occupancy stages such as demolition (Elmaraghy et al., 2018), rehabilitation (Pereira & Cachadinha, 2011), and facility management (Bascoul et al., 2018).

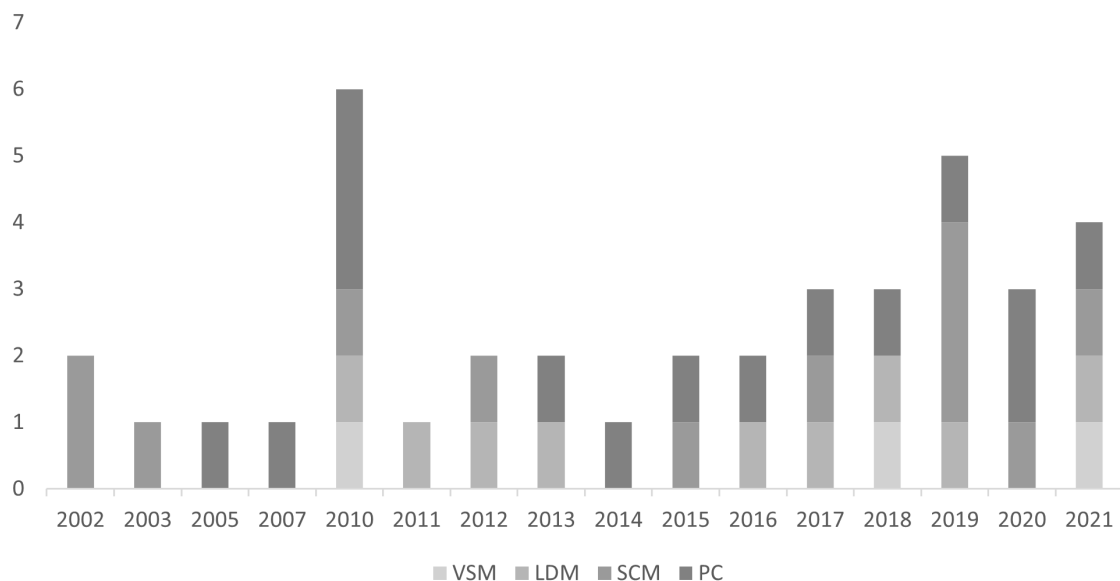


Figure 2-7 – Time analysis of empirical research from 2002 to 2021.

2.5. Results

This section describes the elements of lean construction that tackle waste by answering the three questions elaborated on in (section 2.2). Firstly, to answer the RQ1, Section 2.5.1 and Section 2.5.2 discuss lean approaches to understanding construction waste concept, nature, and taxonomies and summarise LC principles for waste elimination. Apart from depicting theoretical foundations of waste elimination from LC perspectives, qualitative and quantitative empirical literature are classified according to Integrated Lean Project Delivery stages in subsection 2.5.3. Subsection 2.5.4 explores potential research gaps of waste in LC research from sustainability prism. Subsection 2.5.7 reviews BIM history, definition, and integration between LC and BIM. Subsection 2.5.8 is an additional literature review on the Portuguese research in LC. Subsections 2.5.8 and 2.5.9 present the discussion and conclusions and detect research gaps and future research from LC-BIM approaches to eliminate construction waste. The subsequent sections summarise waste elimination knowledge in LC and BIM research.

2.5.1. Waste Elimination and Lean Construction

In the Toyota Production System (TPS) philosophy, waste is recognised as an actionable and instrumental concept that generates meaningful information that guides people in revealing causes of inefficiency and potential improvement in their production systems (Ohno, 1988). Ohno taxonomised waste into seven classes: (1) overproduction, (2) transportation, (3) inventory, (4) motion, (5) waiting, (6) overprocessing, and (7) defects. This list has been adopted in industries other than the manufacturing industry, including the construction industry. In the construction context, LC provided several taxonomies based on this list:

- TFCV-based taxonomy (Bølviken et al., 2014): re-arranges each type of waste according to Transformation, flow, and value theory. This classification addresses the construction context, which can assist construction managers in locating each waste according to the level of analysis provided; however, this taxonomy remains a generic taxonomy that does not tackle waste at specific stages of the construction supply chain.
- Dominance-based classification (Koskela et al., 2013): This classification focused the most on the level of impact on production outcomes if one waste from this taxonomy arose and addressed the peculiarities of the construction projects, which could influence decision makers to determine which waste should be prioritised while taking waste elimination actions. However, this classification could not track the propagation of waste across the different stages of the construction lifecycle and did

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not provide any basis for measuring or analysing waste.

- Propagation-based list (Fernández-Solís & Rybkowski, 2012; Formoso et al., 2015), this list tracked the construction waste from emergence until the state of discovery for construction waste, providing insights on the dominance of waste and broken down waste into Flow-based classification. However, this list did not provide any basis for measuring or analysing waste, and there was a lack of focus in construction stages other than construction and logistics.

Such taxonomies can formalise the understanding of construction waste across manufacturing, logistics, design, installation, handover, use, and post-occupancy phases. Additionally, it is a guideline that increases stakeholders' situational awareness, encouraging practitioners to participate in tracking, analysing, and proactively eliminating construction waste.

Concerning the relationships between waste types, the interdependencies among waste cycles inherit the characteristics of interdependencies between processes, i.e., pooled, sequential, or reciprocal (Formoso et al., 2020). Also, waste can be understood as discrete (task-level), synergistic (project-level), and systematic (organisational and contractual level) (Fernández-Solís & Rybkowski, 2012). Systematic waste is related to loosely coupled stakeholders (fragmentation), which is relatively difficult to defeat with traditional management approaches without continuous improvement efforts. Formoso et al. (2020) categorised the construction waste into 1) previous stages (design, planning and control, material supply and training), 2) production wastes (quality deviation, making-do, transportation, waiting, work-in-progress, inventories), and 3) terminal waste or traditional waste metrics (rework, defects, material waste, safety issues, gas emissions).

Table 2-2 defines production wastes based on Formoso et al. (2020); this study realises that waste can be mapped into unidirectional or singular directions and bidirectional relationships, comprising complex waste networks or chains. As the process's complexity rises, the waste propagated is more multifaceted (Formoso et al., 2015). However, the study did not depict causality between different wastes but showed the patterns of waste prorogation. The wastes shown in Table 2-2 can be used as generic metrics to track production bottlenecks and as a communication tool to highlight the potential improvement in the production system. It is critical to identify wastes as a starting point to apply lean principles, methods, and techniques, which support decision-making for overall performance improvement by compressing cycle times and streamlining value-added activities.

Table 2-2 – Construction production waste categories according to (Formoso et al., 2020)

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Waste	Definition
Making Do	Negative productivity occurs when the task is started or continued without the full availability of inputs. It may cause decisions such as excessive use of resources to compensate for delay or shortage (firefighting) or leaving unresolved issues in a specific task and moving to another task (low-fruit-gripping).
Quality Deviation	Excessive-quality variations arise in resources, suppliers, products, inefficient deviation detection mechanisms, and poor client value capture.
Transportation	Poorly coordinated transport caused the resources to be inefficient, including transportation operations, setup, and equipment use.
Inventory	It is the status of accumulated unfinished products between the start and end of a product routing. It hides quality problems.
Work-in-Progress (WIP)	WIP is the number of incomplete and necessary upstream tasks preventing successive processing activities. According to Little Law, WIP is an important production factor that can be determined through the relationship with cycle time.

2.5.2. Lean Construction Principles for Waste Elimination

Lean construction (LC) has become a relevant philosophy in modern construction management education, research, and practice (Forbes and Ahmed, 2010). The LC community sees that the root causes of fragmentation in the construction supply chain (CSC) are caused by the conventional 'Transformation' construction management model. Hence, that requires more emphasis on 'Flow' and 'Value'(Koskela, 1992). The flow view of production decomposes the construction processes into manageable pieces to reveal and measure waste in processes, operations, and tasks. At the same time, the value view centralises the construction production system by simultaneously capturing and delivering customer value without waste.

LC project management refers to temporary production systems structured to deliver the product with maximised value and minimised waste (Ballard & Howell, 2003). Akin to lean production, LC means and ends are built on lean principles with some adaptations to the construction context. Among these principles, waste is addressed directly and indirectly within the following eight principles. (1) Reduce the cycle time, (2) Reduce variability, (3) Continuous Improvement, (4) Increase Transparency,

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(5) Reduce batch size, (6) Reduce rework, (7) Reduce Inventories, (8) Reduce Defects (Koskela, 2000; A. Santos, 1999). That can be clustered into four direct principles: 'reduce cycle time,' 'reduce variability,' 'continuous improvement,' and 'increase transparency,' as shown in Figure 2-7 and described in Table 2-2 with the corresponding goal of each principle-related theory and potential methods. Ballard and Howell (2003) envisioned that even partial application of these principles could hold disruptive benefits of waste elimination across the whole CSC.

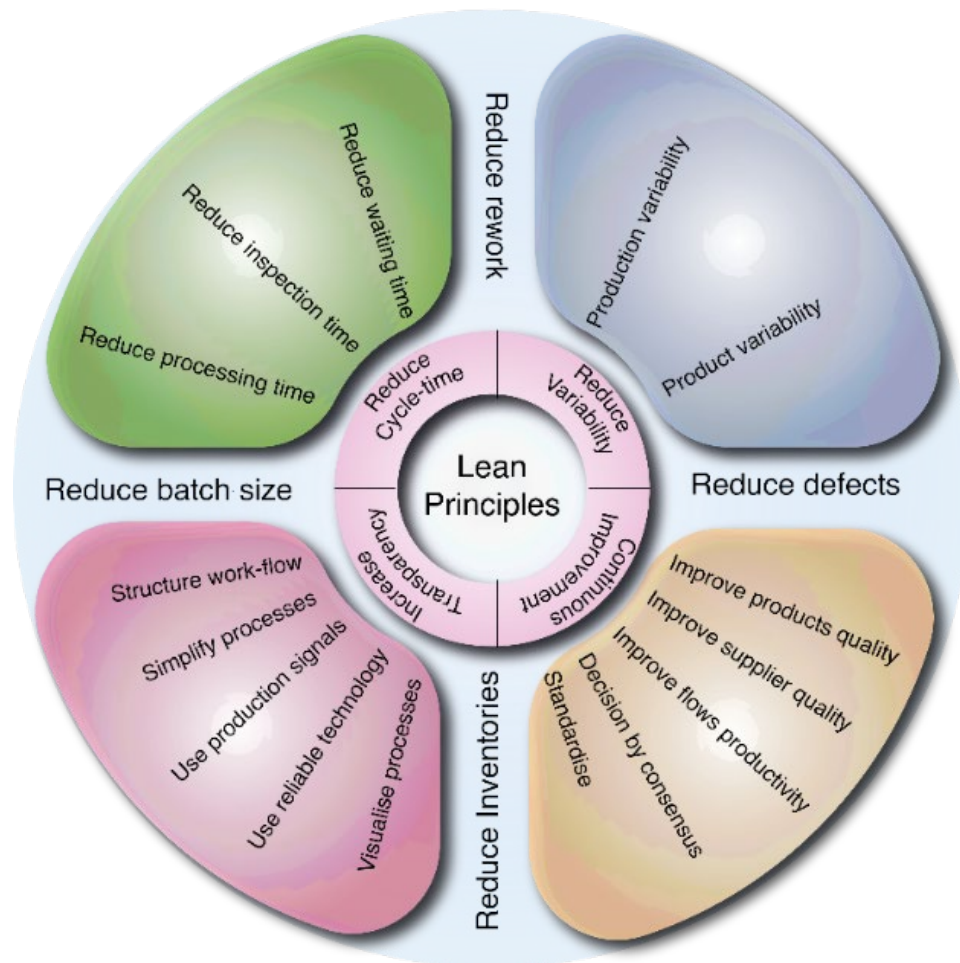


Figure 2-8– Lean Construction principles clustered according to waste elimination concept.

2.5.3. Integrated Lean Project Delivery

Integrated Lean Project Delivery (ILPD) is a project delivery system that plans the whole lifecycle based on lean thinking, as proposed by Ballard and Howell (2003). ILPD comprises five interconnected stages: 1) project definition, 2) lean design, 3) lean supply, 4) lean assembly, and 5) lean use. The project definition is a strategic phase that seeks to capture the client's value (requirements, needs, specifications, and purposes) and to align them with stakeholders' purposes and means. Firstly, an

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adequate project definition must invite all representatives of the whole life cycle of the building for a conversation. At this stage, a value alignment should be reached between customers and stakeholders to define design criteria. Secondly, the lean design interacts with project definition to define product and process design goals for functional systems. When new opportunities are revealed during design research, it is possible to go back to the project definition if they are consistent with the customer and stakeholder's constraints. Lean design urges deferring the design decisions until the last responsible moment to allow the decision makers to generate more alternatives; this strategy attempts to absorb the impact of project uncertainty and complexity, which can prevent rework and disruption of design tasks. The design decisions must be made within the lead time to realise alternatives. The third stage of ILPD is Lean supply, which interacts with detailed engineering and consists of fabrication and delivery. Lean supply management aims to reduce the lead time for material and information flows by determining pace and delivery time. The fifth stage is Lean assembly, which begins with the delivery of material and information on installation and finishes when the client has beneficial use of the facility; it happens after commissioning and start-up. Figure 2-9 depicts that the role of production extends from project definition to lean assembly, which are the core functions of production management by lean.

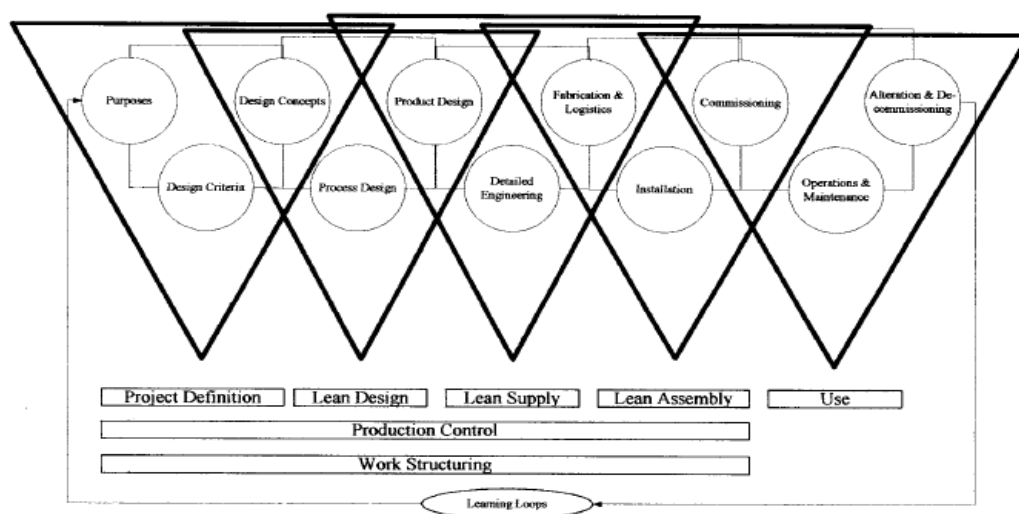


Figure 2-9– Integrated Lean Project Delivery (LPDS) (Ballard & Howell, 2003)

Lean Supply Chain Management

The construction supply chain (CSC) generates significant physical and process waste. This waste encompasses various aspects such as material waste generation (Yuan & Shen, 2011), GHG emission release (UN, 2017), and excessive non-productive time (Horman & Kenley, 2005). These inefficiencies

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are often attributed to a lack of understanding and effective management of the peculiarities of CSC projects, and the peculiarities are one-of-a-kind, make-to-order, project-based, site-production and temporary organisation as explored by Vrijhoef & Koskela, (2000). Moreover, many factors characterise CSC production and inconsistent organisational structures, leading to conflicting stakeholder goals and needs (Howell & Ballard, 1998). The fragmentation within the CSC introduces multiple potential sources of waste, including transportation inefficiencies, congestion, double-handling, excess movement, and waiting times (Björnfot & Jongeling, 2007; Pérez & Bastos Costa, 2021).

Lean supply chain management (LSCM) embraces JIT (Just-in-time) principle to minimise lead time, inventories, and variabilities throughout the whole supply. At the urban level, LSCM advocates for relocating the role of the supply away from the construction sites by increasing the use of prefabricated components. Additionally, it recommends implementing decoupling methods for delivery processes, such as consolidation or terminal centres; decoupling methods seem to enhance the reliability of the buffer between the supply and site demand, as depicted in Figure 2-10. Construction Consolidation Centers (CCC) act as storage hubs for kitted packages before they are delivered to the site, facilitating reverse logistics (Elfving et al., 2010). This strategy enables the construction industry to limit transportation waste, adding value to productivity and sustainability within a circular economy framework (Vrijhoef, 2020). At the logistics level, workspace management allocates resources according to their spaces, storage, areas, routes, and paths (Pérez & Bastos Costa, 2021). At the same time, the production demand is provided by signals from lean planning and control systems (e.g., LPS and LBMS). These systems prioritise pulling work packages rather than pushing work downstream, ensuring that between-handoffs trade discussions are initiated and resolved promptly.

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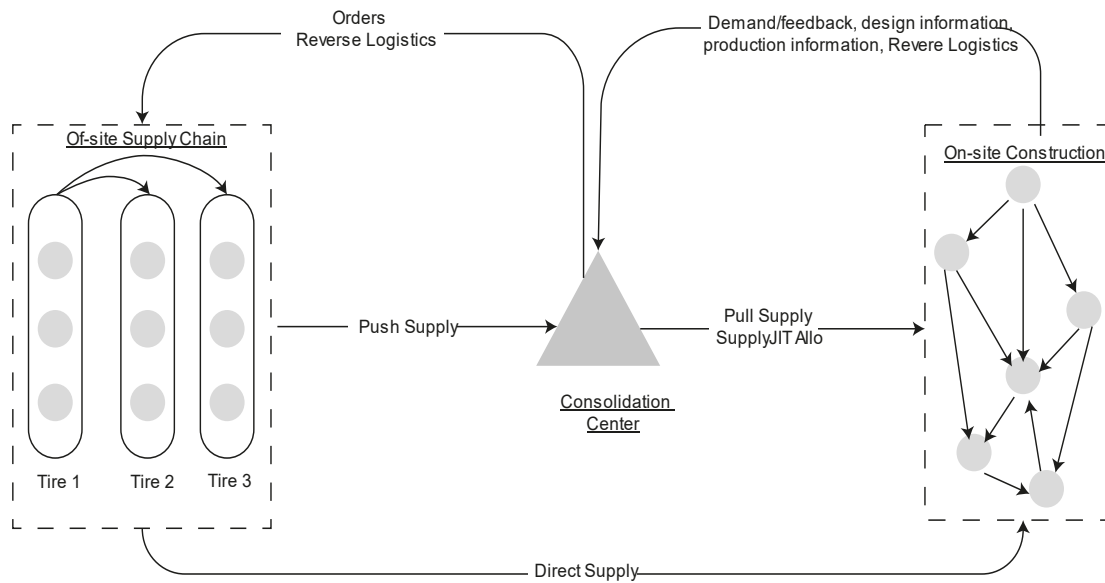


Figure 2-10– Illustration for the role of Construction Consolidation Centres

Lean Design Management

Lean Design Management (LDM) provides simultaneous design processes that focus on diminishing waste collaboratively at the earliest stages of BIM projects using social, technical, and socio-technical dimensions (Barkokebas et al., 2021; Uusitalo et al., 2019). The social dimension urges people to adopt BIM and enhance their collaborative production skills based on trust and shared understanding among the involved parties (Arayici et al., 2011). At the same time, the socio-technical dimension eliminates waste in terms of planning and control, customer requirement management, decision-making methods, and problem-solving techniques (Herrera et al., 2021; Uusitalo et al., 2017). Again, the production indicators are used in LDM to quantify NVA in design workflow and information flow.

The current practice plan for design tasks is Kanban based on software but without complete reflection of LC-BIM integration (Mahalingam et al., 2015). This practice disregards opportunities for BIM functionalities specific to the construction design context. This research recommends more research on applying LDM planning and control methods in a BIM environment to apply waste elimination concepts. At the same time, the research lacks integration of waste elimination in LDM customer management methods, which can potentially steer design processes and products toward customers' value and waste elimination by utilising techniques such as Target-Value-Design (TVD), Choosing-By-Advantage (CBA) and Set-Based-Design (SBD) (Karaz & Teixeira, 2023a).

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Last Planner System

The primary objective of the LPS® is to provide reliable production planning that shields downstream from upstream variability (Ballard, 2000). LPS is defined as a socio-technical system that unites the stakeholders, including 'the last planners' or the last responsible people, to optimise production plans in successive detailed levels (Ballard, 2020). Figure 2-11 illustrates the structure of LPS, which divides the planning into four successive levels: Master scheduling (Should), Phase planning (Can), Lookahead planning (Will), weekly, bi-weekly, or daily planning and learning (Did). Master scheduling is an overall project schedule from start to finish, which identifies Activities On Nodes (AON) using the CPM method that delimits the project scope. The knowledge of a master schedule is fed by historical data or practitioners' experience; a master schedule is used as a contractual schedule to sublet works to subcontractors, assess the project feasibility, identify long lead times, and identify milestones to be used in the next stage "phase planning" (Frandsen et al., 2013).

Lookahead planning spans 4-6 weeks, collaboratively deriving sub-tasks from the milestone schedule, detecting and delegating responsibility to constraints, and thus, trades commit to removing these constraints (Ballard 2000). In the weekly work planning (WWP), the team screens constrained tasks and excludes them from the execution schedule. To streamline continuous and stable flow, LPS practitioners commence working on mature activities only, and a quality check for work backlog is applied for work package definition, soundness, sequence, size, and learning (Ballard & Howell, 1998). In the lookahead planning window, constraints analysis is a critical function of LPS. According to (Koskela, 1999), the constraints of the construction products are seven (1) design, (2) components, (3) materials, (4) materials, (5) space, (6) connecting works and (7) external conditions. Similarly, (Ballard & Howell, 1998) classified the constraints into three clusters: (1) directives: necessary information to commence processing (i.e., specifications, product designs, crew numbers, and speciality, among the others), (2) previous works: prerequisite work that must be finished before starting new work and (3) resources: including labour, equipment, support facilities, materials, and space.

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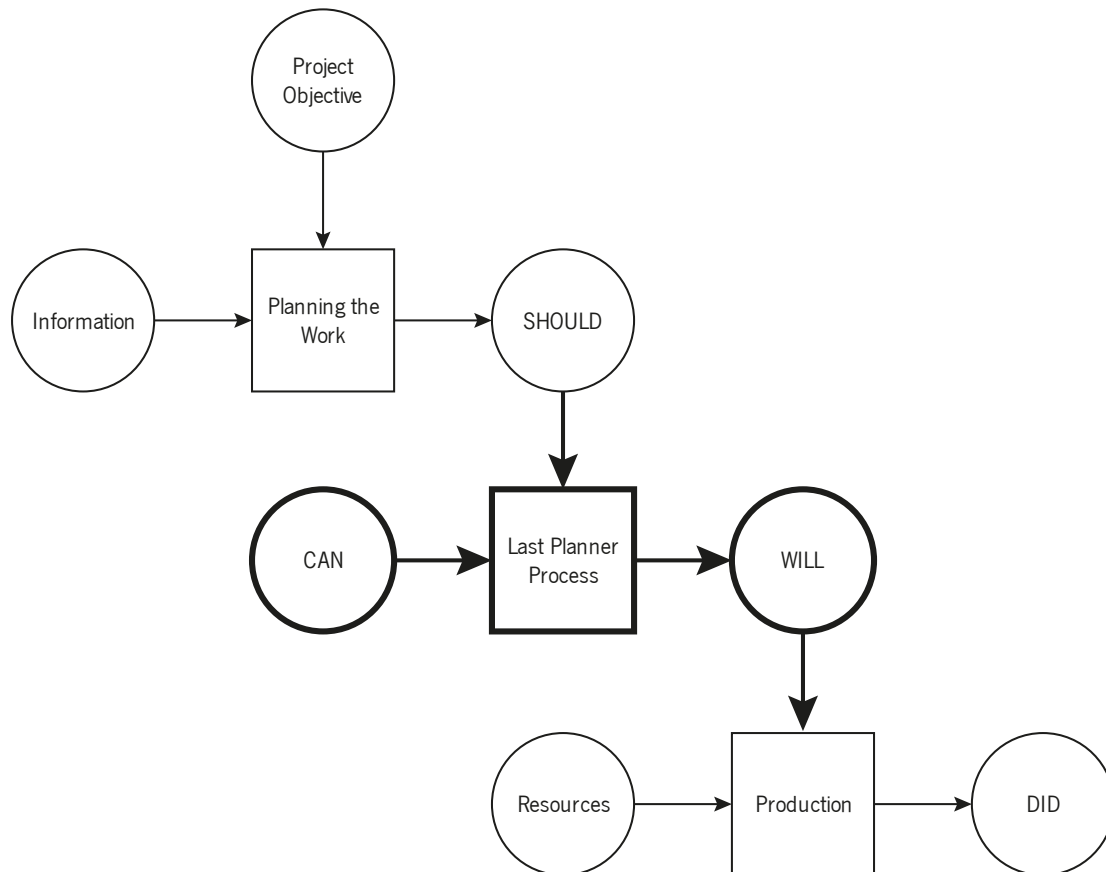


Figure 2-11– A generic framework for the Last Planner System (Ballard & Howell, 2003)

During meetings to screen tasks and constraints, a language/action can be used to formalise the communication for commitments between trades to describe, request, declare, promise, or assert specific information about work packages (Macomber et al., 2005). Control indicators such as PPC are used to measure the reliability of promises, which is the percentage of work completed divided by the promised work, which helps investigate and learn potential production bottlenecks (Sacks, Korb, et al., 2018). The LPS practice can diminish wastes such as making do, moving, waiting, transportation, inventory, reworks, and defects. Hence, LPS formalises communication between multidisciplinary trades during work structuring, sequencing, constraint removal, control, and learning.

Information synchronisation is necessary to implement LPS, primarily by increasing the planning details to enlarge the immense amount of information that can be retrieved into the system, which can be tackled using BIM functionalities such as 4D planning, clash detection, and site layout planning (Dave & Sacks, 2020). Lean-BIM-based production planning and control systems PCS can streamline flexible production systems that actively respond to bottlenecks. Waste should be revealed and

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understood by improving situational awareness, activating root causes of waste, performing what-if scenarios, and activating real-time tracking for production bottlenecks.

	SHOULD	CAN	WILL	DID	
Planning Stage	Master	Phase (Pull)	Lookahead	Short-term	Learning
Planning Window	Milestones	Phases	4-6 weeks	Weekly/Bi-Weekly/Daily assignments	
Planning detail	 Rocks (Milestones)	 Rocks (Phases)	 Boulders (Processes)	 Pebbles (Operations)	 Pebbles (Assignments)
Main activities	- De'fine key milestones - Identify critical path (CPM) - Assign start-'inish relations	- Apply reverse planning - Identify handoffs, durations, and overlaps - De'fine delivery conditions	- Constraint analysis - Breakdown Processes - Design for operations	Make reliable promises	- Measure PPC* - Investigate RNC** - Standardize
Addressed wastes	- Budget overrun - Schedule overhead - ENV measures - Value measures - Defects	- Budget overrun - Schedule overhead - ENV measures - Value measures - Defects	- Making-do - Work-in-Progress - Inventory - Crews absent, injuries - Transportation - Information delay - Rework	- Idle (waiting) - Un'inished works - Rework - Moving	PPC Failures
Actors	- Owner - Portfolio Managers - Project Managers	- Project Managers - Site/production Manager	- Project Managers - Site/production Manager	- Project Managers - Site/production Manager - Crew managers	- Project Managers - Site/production Manager - Crew managers

*PPC = Plan Percent Complete; RNC = Reason for Non-Compliance

Figure 2-12 – Last Planner System stages, durations, details, main activities, addressed wastes, and responsible parties.

Additionally, location-based management systems (i.e., takt-planning, flow line, Line-of-Balance) can be applied to structure even and steady workflows across locations of the construction product, supported by 4D functionality to provide additional insights about work sequencing, related time, and spatial conflicts (Björnfot & Jongeling, 2007). The available digital tracking methods are enabled for site conditions by LPS and BIM, including surveying methods, laser scanning, indoor positioning, GPS, BLE Beacon, IoT techs, stationary touch screens, PDAs, mobiles, tablets, and RFID (Chen et al., 2020; 2016; Sacks et al., 2010; von Heyl & Teizer, 2017). These technologies deliver additional prospective opportunities in automatic waste elimination decisions through artificial intelligence (AI) algorithms, according to the increasing waste data that can be extracted from Lean planning and control systems, which are requirements for system learning, testing, and validation (McHugh et al., 2022).

Location-based Management Systems

The goal of Location-based Management Systems (LBMS) is similar to that of LPS, which is to streamline reliable planning and control by planning for continuous workflow and preventing interference between trades. Nevertheless, LBMS is a scheduling and control method rather than LPS and depends on technical measures, unlike LPS, where social measures are apparent. LBMS is preplanning, planning,

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scheduling, and controlling systems for production units based on their physical location (Kenley & Seppänen, 2010).

The LBMS process comprises scheduling, schedule optimisation, forecasting, alarming, and control. The first step of scheduling using LBMS is defining Location-Based-Structure (LBS). LBS is the method of breaking the project into manageable locations, similar to Work Breakdown Structure (WBS), but applied to location logic instead of activity-based logic. Each task is defined at a specific hierarchy level and includes one or more locations (Kenely and Seppanen, 2010; pp 125-126). Defining LBS is a critical decision because it is not only necessary for LBMS purposes (e.g., defining logical relationships, visualising flow line, and controlling the progress), but it could also be applicable for classifying quantity-take-offs and signalling logistics and deliveries (Kenley & Seppänen, 2010: PP 203-204). In the example elaborated in Figure 2-13, LBS first breaks down the project into interdependent structures that can be built separately, then narrows it down to manageable locations where one trade can operate continuously without interruption (waiting). Where actors can filter and communicate activities based on this LBS code.

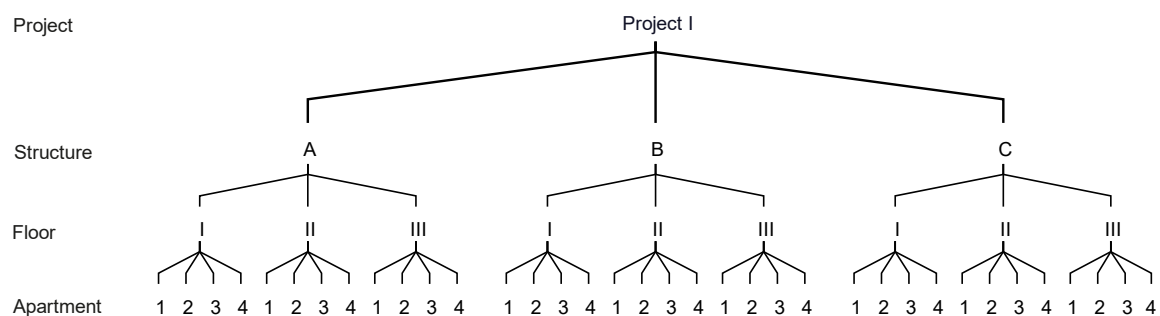


Figure 2-13 – A generic example of LBS hierarchy for a building project (Kenley & Seppänen, 2010)

Accurate estimations of quantities are critical to calculate the schedule durations. Calculating quantities is a subsequent step in LBS definition in LBMS scheduling. The task quantities must define all the work to be completed in a location before a crew moves to the following location. Then, LBMS builds tasks from quantities, defines optimum crew size, and uses layered logic for other tasks. Durations are computed by multiplying quantities with labour consumption and dividing by the crew size.

Schedule alignment and optimisation through risk management expand trade-offs between time, risk, and cost sought by alignment, making planning tasks continuous and buffering tasks against interference. LBMS optimises the plan to ensure workers do not wait for work and work does not wait

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for workers. LBMS needs more data than CPM, and LBS needs to be defined beforehand. At the same time, CPM methods are a free form of planning; they report weekly or daily, while CPM is monthly and LBMS is real-time control. The strategies used for schedule optimisation are 1) changing production rates, 2) adding more resources, 3) splitting tasks, 4) allowing discontinuous work, and 5) adding more for the scope or reducing resources.

Besides scheduling information, LBMS also provides controlling information. This information includes baseline schedule, current stage, progress, forecasting, and alarms. The baseline schedule is an owner reporting tool that sets limitations to the current schedule. The current stage enables changing quantities, productivity rates, logic, and planning during production, where each task (detailed task) is linked to one baseline task for comparison reasons. The progress stage monitors the actual performance of the project/location/tasks. In this stage, actual dates do not replace planned ones but are used to compare and detect variations. (Input) in start and finish dates, suspended days, and actual resources, while the (output) is calculated as 1) actual resource consumption and 2) actual production rate (units/day/trade). The forecast combines the current and progress stages information to signal early warning about production problems by assuming that the production will continue with the same productivity and with the planned resources and follow the current logic. LBMS alarms show when the predecessor delays the forecast of a successor. Alarms are two weeks before the planned time (Kenley & Seppänen, 2010: 123-126), that attempt to prevent cascading delays by concentrating production control resources to avert these alarms from happening and correcting the predecessor's production rate or slowing down the successor.

In LBMS, stakeholders can reduce the number of interdependencies between activities provided by CPM methods, remove float between tasks and synchronise production rates. LBMS can apply several control indicators to forecast production capabilities and provide information about root causes of cascading delay (i.e., work-in-progress, waiting, rework, and congestion) (Kenley & Seppänen, 2010). Finally, LBMS reduces production complexity by streamlining continuous flow across locations, steering planning targets towards stable and interrupted production, giving clear directions for trade crews, and reducing risk and waiting time (Biotto & Kagioglou, 2020).

The comparison conducted by Biotto and Kagioglou (2020) highlights Lean-Based Management System (LBMS) techniques as prominent management methodologies in both the master and phase planning processes. Within master planning, the Line of Balance (LOB) and Flow Line (FL) techniques are commonly applied. LOB primarily focuses on monitoring the delivery rate of completed units, with

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planners allocating production capacity buffers within the duration of work packages per unit between activities. This monitoring function enables LOB to balance production by adjusting the number of crews assigned to specific activities and modifying the composition and quantity of work to be executed.

In contrast, the Flow Line (FL) technique is more oriented toward production pace planning, with actors allocating buffers for production capacity within task durations. The principal strategy of FL involves modifying the crew's composition. The slope of FL defines the production rate, calculated by dividing the work quantity by the duration. FL is typically employed in repetitive construction scenarios but can also be applied in complex projects, provided the project can be effectively segmented into equal locations.

On the other hand, the Takt Time planning (TTP) technique is commonly used in phase planning because it provides more significant planning details than FL and LOB and requires a higher level of collaboration. TTP is defined as 'the unit of time within which a product must be produced (supply rate) to match the rate at which that product is needed (demand) rate' (Frandsen et al., 2013). It is measured using the Takt Time (TT) indicator, which can be obtained by dividing the available production time by the product units demanded by the customer. The primary buffer strategy used in TTP is like the FL method, which uses a production capacity buffer that urges actors to insert different compositions and numbers of workers within the work package.

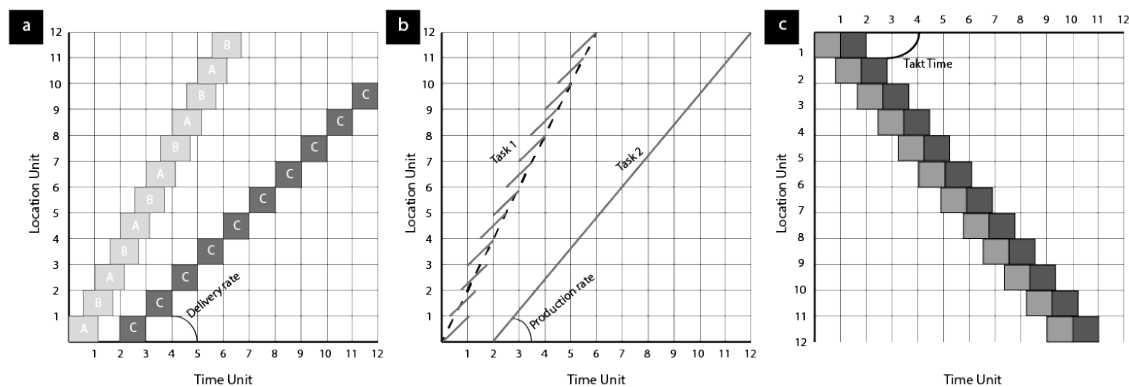


Figure 2-14 – Visualisation comparison between three LBMS techniques: a) Line of Balance; b) Flow Line; c) Takt Time (Biotto & Kagioglou, 2020)

2.5.4. Relational and Legal Structures for Waste Elimination

Legal bonds between parties are essential in guiding construction organisations toward value creation and waste generation (Koskela, 2000). Relational contracts emerged and flourished in the late 20th century to facilitate a road map for construction improvements. Integrated Project Delivery (IPD), Integrated Forms of Agreements (IFOA), Partnering, and alliance contracts are examples of Relational contracts that may tackle construction waste by cultivating collaboration in defining clear assignments and responsibilities toward project goals that align the interests of multiple stakeholders to optimise their projects globally instead of focusing on local optimisation for the production.

Partnering contracts reduce the liaisons between actors to resolve issues and involve the downstream in upstream decisions through improved collaboration and transparency. Material waste is highlighted in partnering contracts by imposing a material waste management plan (WMP), but the terms of partnering contracts lack focus on production waste elimination (Matthews et al., 2000). In contrast, alliance contracts support task completion, manage inventory and toolbox sharing, and allocate responsibilities where lean principles apply to decompose complex wastes and discard NVA through tools such as 5whys, waste walks 'Genchi nembutsu,' spaghetti diagrams, quality control histograms and Root Cause Analysis (RCA). Combining lean principles and relational contracts can eliminate about 24% of NVA by facilitating double learning, improving process quality, and implementing safety measures (Vilasini et al., 2014). However, alliance procurement lacks explicit terms for waste elimination, which causes an absence of legal commitment and measures toward waste recognition, analysis, and responsibility for waste elimination. More research is needed to include the concepts of waste elimination in relational contracts, and this gap can also be applied to IPD, alliance contracts, and collaborative Design-Build contracts.

2.5.5. Lean Sustainability

From the LC perspective, environmental waste encompasses adverse outcomes within the production system that fail to contribute value to the final customers (Formoso et al., 2015; Koskela et al., 2013). Practices associated with LC have demonstrated the potential to enhance production efficiency and sustainability performance (Kim & Bae, 2010; Rosenbaum et al., 2014; Saieg et al., 2018). Provides evidence elucidating various approaches to studying the impact of lean construction on reducing environmental waste, showcasing reductions achieved in each study. However, it is worth noting that

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specific lean methods, such as Just-in-Time (JIT), may inadvertently lead to increased carbon emissions due to frequent shipments required to maintain zero-inventory conditions (Hussein & Zayed, 2020). Moreover, a comprehensive solution for effective facility management with a lean management philosophy has not yet been investigated (Elmaraghy et al., 2018).

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Table 2-3 – Comparative analysis for the integrated methods with VSM to investigate construction wastes.

Author(s)	Method	Material waste	Carbon Emission	Energy consumption		Water	Landfills
				Fuel	Electric		
(Golzarpoor et al., 2017)	DES-I/O	●	41%	41%	-	-	●
(Fu et al., 2015)	LCA	-	42-44%	-	-	-	-
(Wu et al., 2013)	Low carbon lean system	●	29.39%	●	-	-	●
(Kim & Bae, 2010)	CEDST	●	10-20%	●	●	-	●
(Rosenbaum, Toledo and González 2014)	VSM	50 to 100%	●	●	-	-	100%
(Belayutham, González and Yiu 2016)	VS-PM	●	-	-	-	●	-
(Vilventhan, Ram, and Sugumaran, 2019)	VSM	13.18-57.37%	-	-	-	-	●
(Nahmens and Ikuma 2012)	SLIK	64%	●	●	●	●	●

DES-I/O = Discrete Event Simulation – Input/output; LCA = Life Cycle Analysis; CEDST = Construction Environmental Decision-Support Tool; VSM= Value Stream Mapping; VS-PM = Value Stream-Process Map; SLIK = Safety and Lean Integrated Kaizen; ● = reported reductions without percentage

2.5.6. Value Stream Mapping

Applying the Value Stream Mapping (VSM) method is indispensable for lean initiatives, offering a structured approach to visualize information and material flows while identifying potential improvements through waste elimination principles (Womack & Jones, 2003). Through data collection of production indicators sourced from involved stakeholders or via direct surveys and observations, two distinct VSMs can be developed: current and future maps. Both maps rely on key performance indicators such as NVA (Non-Value-Added), CT (Cycle-time), WIP (Work-In-Progress), Takt Time (TT) and Queuing Time

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(QT) (Nahmens & Ikuma, 2012; Rother & Shook, 2003). Notably, VSM can address various types of construction waste across the Construction Supply Chain (CSC), encompassing injuries/accidents, material waste, transportation, waiting, quality deviations, rework, defects, and environmental waste (Nath et al., 2015; Rosenbaum et al., 2014; Vilventhan et al., 2019).

However, it is essential to acknowledge the limitations associated with VSM review, particularly concerning the context-specific nature of waste data collected from operational-level professionals, limiting broad generalisation (Viana et al., 2012). In response, some researchers have turned to alternative methodologies such as Discrete-Event-Simulation (DES) and Agent-based-Simulation (ABS) to enhance the waste elimination process within the VSM framework (Golzarpoor et al., 2017; Al Hattab & Hamzeh, 2018) in addition to the association of VSM with System Dynamics modelling, it has been used to investigate the accumulation of NVA waste across the project time at the strategic level (C.-H. Ko & Chung, 2014). Nevertheless, the adoption of simulation methods is hindered by perceived time constraints and a predominant focus on academic applications (Erikshammar et al., 2013).

Furthermore, integrating VSM with BIM processes presents a compelling avenue for enhancing transparency and meaningful visualization. By evaluating NVA activities, VSM enables construction stakeholders to identify and mitigate waste sources within their processes collaboratively (Michaud et al., 2019). Specifically, VSM decisions can shed light on the constraints within the BIM workflow, facilitating shorter BIM execution durations through streamlined design reviews and verification processes and reducing waiting times for information (Nath et al., 2015).

Despite the evident benefits of investigating waste in BIM-based design management using VSM, the current literature underscores a notable absence of automated solutions capable of extracting BIM information for use in VSM and vice versa. Such integration is crucial for effectively leveraging production metrics to control the waste of BIM implementation processes.

2.5.7. Building Information Modelling as Lean Construction Enabler

BIM becomes a *de facto* technology, process, and behaviour that supports digitisation within the AECO industry to handle the fragmentation and complexity of the construction information inflow. Stakeholders are a source of information collection, generation, integration, coordination, and analysis of the construction product and process. BIM gradually replaces traditional design tools because of its capability to overcome significant root causes of construction waste, such as design inconsistency,

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errors, duplications, poor quality, increased costs, construction waste, rework affected by paper-based and 2D-CAD (line-based) design methods (Sacks et al., 2018). BIM has the potential to support organisations in managing their work efficiently, as well as address the challenges of the AECO industry and improve its productivity.

Brief BIM history

Charles Eastman, 1970, first proposed the concept of BIM. Initially, it was termed the Building Product Model and was seen as software containing a database for building elements. By 1975, Eastman proposed another prototype, the Building Description System. BIM saw its workable software within a construction project in 1987 under the auspices of Graphisoft. This application marked the creation of a virtual model using ArchiCAD, recognised as the first BIM-related software. Later, integrating information management with existing CAD technologies facilitated the evolution of BIM into its existing form. With the growing acceptance of BIM-related processes within the industry, a surge in research and software development endeavours emerged. These efforts have significantly shaped the construction sector's current understanding and application of BIM.

BIM definition

The rapid evolution of BIM technologies and concepts has led to a multitude of definitions of BIM, with no unique definition of it, varied to the different perspectives of the authority or individuals provided this definition of BIM; the United Kingdom National Building Standard (NBS) defines BIM as "a digital creation and management of information on a construction project throughout its whole life cycle" (NBS, 2018). In comparison, ISO (International Organization for Standardisation) referred to BIM as a shared digital representation of a built asset that facilitates design, construction, and operation processes and forms a reliable decision basis (ISO, 2018).

BIM offers a high-accuracy representation of a construction project, allowing simulation of the project in computerized engines before the execution and producing high-performance and less error-prone construction (Liu et al., 2016). It also provides data for stakeholders' decision support and facilitates real-time collaboration, improving work efficiency, effectiveness, and productivity (Chahrour et al., 2021). Among the features of BIM is supporting collaborative production and exchange of the construction information from the earliest stages of the construction project until handover and facility management, which adds value for the digital asset for the construction, shifting traditional sequential

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processes to a central model where all stakeholders work individually but are always connected. This paradigm shift will benefit society through better construction projects that consume fewer resources and operate efficiently (Andújar-Montoya et al., 2020).

Recent international standards such as ISO 19650 and 12006 describe the BIM process and associated data structures (ISO, 2018). ISO 19650 and ISO 12006 have become necessary standards in reducing waste and lean construction thanks to the normalisation of information management procedures, functioning as productive cooperating, increasing data-driven decisions, uniting with lean thinking, and progress of constant improvement (Sheramn & Kirwan, 2019). The standards will serve as the compilation guidelines on authoring construction documents with clear communication, taking the lead since it involves all stakeholders in the project and minimises delays and conflicts. Through the reiteration of data precision and dependability elements for choosing between options, they can tackle the roots of wasting more efficiently. Furthermore, when applied and aligned with lean construction methods, they cut down on workflow timeframe, ensure just-in-time principles, and allow a progressive goal-oriented approach towards reducing waste generated throughout the project lifecycle.

BIM and Lean

A successful BIM implementation and development should stand on three high-level pillars: process, people, and tools (Figure 2-15). According to Hardin & McCool (2015), technology represents only one-third of overall BIM implementation, which impedes the need to focus on people and processes as equal as the utilisation of overarching technologies. The evidence shows that Lean construction can complement process and behaviour pillars (Sacks, Radosavljevic, et al., 2010; Tommelein & Gholami, 2012; Zhang et al., 2018), while tested and reliable technology is required to achieve lean construction means and ends.

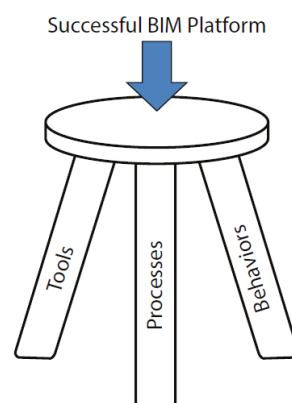


Figure 2-15– Three pillars of successful BIM implementation (Hardin & McCool, 2015)

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Lean construction and BIM are developed and adopted concurrently, and much research has shown that their implementation is interdependent (Al Hattab & Hamzeh, 2015; Barkokebas et al., 2021; Bhat et al., 2018; Gerber et al., 2010; Oskouie et al., 2012). Based on the surveyed literature by Sack et al. (2010), there are 54 positive interactions between LC principles and BIM functionalities to boost productivity and deliver value to external and internal customers. Hence, production systems can be designed, planned, and controlled based on coherent and consistent information on products and processes. In terms of tools, the critical functionalities of BIM that support LC implementation in Figure 2-16 are clustered into five significant functionalities, namely, 1) parametric Modelling, 2) documentation, 3) quantity-take-off, 4) bidirectional connectivity, and 5) simulation.

BIM construction management

The BIM-based construction management software has spatial and temporal coordination capabilities and scales up the presented information to load time and cost data on the model, called 4D and 5D BIM (Sacks et al. 2018). Also, models can show file attachments and advanced detailing for prefabrication and installation information, easing product and process understanding across the construction supply chain. Interoperability is a significant advantage in implementing BIM since multidisciplinary teams can work simultaneously on the same project. Because of the proactive prevention of space and trade clashes, they can federate the project to apply clash detection analysis, a critical waste elimination method to eliminate spatial coordination problems. BIM-based scheduling is usually referred to as 4D planning or phase planning. This workflow imports Gant chart data from scheduling software such as Primavera and MS projects and attaches the 3D parameters to the planned time, which also will coordinate the actual time in 3D view. 4D planning allows stakeholders to simulate the construction based on time, and this can provide insights into the constraints of construction sequencing and constructability.

BIM and Lean Production Planning and Control

The existing BIM construction management software is shown in Table 2-4. Clash detection and 4D planning are the most common functionalities, but Gant-chart-based CPM is still dominant in their application. However, LC-BIM-based applications can magnify production information to operational, task, and location levels, allowing product and process information integration. For example, Dave

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(2013) demonstrated pulling production information at the coal face at the task level, enabling site crews to report production bottlenecks to planners and supplying the production system with actual resource consumption and productivity rates. Similar approaches have been presented in Table 2-3, where the cost/benefit analysis is rarely addressed, and little research has presented product details in their LC-BIM artefacts.

Table 2-4– Current contributions for BIM Construction Management Software and Lean Construction Based BIM

	BIM Functionalities	Parametric Modeling			Documentation			Bidirectional Connectivity			Quantity Takeoff			Simulation						
		Visual Task Information	Location-Based Hierarchy	Object-based Hierarchy	Modelling Temporary Works	Automatic Reports Generation	Detailed Prefab Information	Model Revisions	Object-Based Communication	Interoperability	Models Integration	Simultaneous Access	Automatic Cost Reconciliation	Automatic Schedule Generation	Cost/Benefit Analysis	Clash Detection	4D Planning	Evaluation What-if Scenarios	Constraints Analysis	Visual Product and Process Information
Academic	KanBIM (Sacks et al., 2011)	✓	✓	✓	✓	✓			✓	✓	✓		✓			✓	✓	✓	✓	✓
	VisiLean (Dave, 2013)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓			✓	✓	✓	✓	✓
	LBS-Based BIM (Hagermoser et al., 2019)		✓	✓		✓				✓			✓	✓			✓			✓
	Beam! (Schimanski et al., 2021)	✓		✓		✓			✓	✓	✓	✓	✓				✓	✓	✓	✓
Commercial	ALLPlan (n.d)		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			
	VicoOffice (n.d)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
	Synchro (n.d)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
	Autodesk Navisworks		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			✓
	Teclia Construction Manager		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓			
	Sobiri Model Checker			✓		✓					✓	✓	✓	✓	✓	✓	✓	✓		
	Autodesk 360 Plan				✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓

BIM for lean supply chain management

BIM is a crucial foundation for informed LSCM decisions regarding transportation, inventory management, design, and site production (Vrijhoef, 2020). For example, 4D modelling enables supply planning based on real-time demand from production status (Bortolini et al., 2019). Furthermore, BIM

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facilitates cost analysis, allowing stakeholders to evaluate the viability of waste elimination measures in transportation, movement, and work-in-progress (Vrijhoef, 2020). In addition to cost analysis, leveraging tracking technologies like RFID (Radio Frequency Identification), QR code (Quick Response), and NFC (Near-field communication) enhances the transparency of waste elimination efforts in logistics management (Dave et al., 2016; Elfving et al., 2010). These technologies are essential in harnessing BIM functionalities to track and report waste in logistics management, spanning ordering processes, transportation, congestion, material handling processes, material waste, and accidents. Integrating a Geographic Information System (GIS) with BIM at a corporate level can inform lean decisions regarding transportation routes, supplier selection, and the establishment of decoupling centres (Deng et al., 2019). Lastly, health and safety practices can be enhanced through LC-BIM design for workflows and locations. LC-BIM visualises and filters obstructed and unobstructed workspaces to validate tasks against potential accidents before commencement (Gambatese et al., 2017; Rozenfeld et al., 2009).

2.5.8. Lean Construction Research in the Portuguese Context

The Portuguese construction industry is becoming aware of the potential of Lean Construction (LC) (Peneirol, 2007). The potential of LC is now being recognised as the potential improvement philosophy for the Portuguese construction industry. The Plataforma Tecnológica Portuguesa de Construção (PTPC) has provided practical guides on lean philosophy and widely applicable tools for construction work (PTPC, 2016). A similar practical Lean Construction Guide is presented by Lima (Lima, 2023). Few companies implemented the lean methodology in 2008, and many respondents who applied for LC responded that their companies started in 2014 (Caseiro, 2016).

Among these is the implementation of LPS on a thermal complex in Estoril, Portugal (Proença, 2017), which resulted in a PPC of 60.53%; however, it became hard to support seeing the effect and cultural change as the time was too limited. The application did not have enough training, so it was more about planning than collaboration and problem-solving. Barriers also included human factors, cultural resistance, and PPC underperformance reporting. Pereira used LPS in selected sites in Portuguese construction projects, which ended with positive results regardless of the resistance to change encountered at the beginning of the implementation (Pereira, 2019).

Barros (2010) investigated the linkage between lean knowledge and application within academic and professional contexts of the Portuguese construction industry. However, there are still a large number of professionals who do not have any idea what it means to be a genuine LC. Unfortunately, the significant response by universities in Portugal is that the knowledge of lean construction is

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integrated into university curricula through respondents' enthusiasm for the potential of lean construction. However, few respondents intended to teach lean construction principles in future courses. Surprisingly, 42% of professional respondents do not know what lean construction is, while 58% confirmed that lean is partially or fully applied in their workflow.

Matias & Cachadinha (2010) Evaluated the potentials and barriers to LC adoption in Portugal by interviewing to represent ten contractor companies and identified that the primary cause of delays and waste is Request for Information (RFI). The LC is not well-heard in Portugal, but respondents have shown interest in adopting it and enthusiasm for its potential.

Martins & Cachadinha (2013) Interviewed designers and owners to investigate the root causes of waste and evaluate LC potentials to tackle these problems. Surprisingly, most respondents did not know about the LC; they agreed that traditional procurement and RFI are the most frequent causes of construction waste.

In interviews with owners and designers in Portugal, only a few companies are testing LC, and most companies are unaware of their potential. Portugal's lack of contractual structure leads to lean construction and the perception that meeting deadlines does not allow them to use LC (Martins, 2011). Despite awareness of LC potentials, another survey showed that the lean construction philosophy is not widely applied in Portugal (Pereira, 2014). 53% of lean applications in Portugal are 5s, and kaizen is mainly used in logistics management; 55% of respondents were not interested in learning lean construction philosophy (Caseiro, 2016).

Action research was applied in a Portuguese company, and positive results have been reported for applying lean methods such as Kaizen, visual management, 5s, safety, and team boards (de Sousa, 2019). H. Just-in-time LPS; their work visualised the processes using VSM (Gonçalves, 2009).

Comparative research is also performed. For instance, the adoption of LC philosophy experience was compared between Portuguese and Brazilian perceptions of and (Caseiro, 2016). Another example was studying the Danish experience in LC and attempting to propose a model for the Portuguese context based on this experience (Silva, 2008).

LC is relatively unknown in Portugal (Gonçalves, 2009), and many critical barriers have been reported. 1) Informal planning and resistance to change were reported as critical barriers. 2) lack of top management support bureaucracy, 3) lack of lean awareness and understanding, 4) fear of new things, and 5) poor constraints analysis and lack of commitment to short-term planning (Gonçalves, 2009), 6)

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the research encountered resistance to change and blockage from companies to share information, which are the most ranked barriers (Pedrosa et al., 2023).

2.6. Discussion

By reviewing 54 relevant papers as the systematic literature review framework, efforts were made to ensure a comprehensive understanding of the covered topics, namely, waste elimination, Lean construction, and BIM, by addressing the disadvantages and limitations of a traditional literature review. These included designing a review protocol to avoid ambiguity, increasing search transparency, and identifying the study's suitability for replications. That said, it may be the case that a small number of the databases used (i.e., Scopus and IGLC) may have produced a slightly lower number of found documents. Nevertheless, the findings of this review indicate that waste elimination is a core concept of lean construction philosophy, but when it is integrated with BIM, few results have been reported, especially regarding production waste. Additionally, changing current research on lean construction and BIM does not show explicit guidelines for waste elimination. Understanding the underlying root causes of construction waste was a significant hurdle to building a holistic review of the waste elimination approaches. This assertion agrees with previous research such as (Formoso et al., 2020; Viana et al., 2012), who identified the difficulty of composing a systematic literature review on waste in construction because of four reasons: 1) persistent construction management theories in the current research and practice; 2) a holistic theory that explains waste propagation and its' characteristics is not presented yet.; 3) ambiguity in the reported collection methods for waste data; 4) variety in conceptualisation to address similar types of waste.

2.6.1. How does lean construction conceptualise waste?

The concept of waste in lean construction has been integral since its emergence in 1992, emphasising the imperative of waste elimination for ensuring survival and enhancing the competitiveness of companies (Sacks et al., 2018). Within the construction literature, waste is conceptualised as a set of symptoms of an inefficient production system, including material waste, injuries, capital waste, and energy waste. In addressing waste, the lean construction approach diverges from traditional end-of-pipe and reactive strategies, which merely respond to symptoms of internal waste after its occurrence within a production system. Koskela, 2013 criticised the poor foundations in the construction management research in conceptualising waste and production concepts; even the relationship between them is the

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purely economic view that only sees the world as input and output, which refused to include waste concepts with the existing construction management theories.

Based on the transformation-flow-value theory, lean construction understands waste concerning value and flow concepts in conceptualizing construction waste. The former tends to refine the process of capturing the customer value from any misconception, and the latter utilises a mixture of social and technical methods to reveal the construction flows and expand the transparency to see wasteful (NVA) and not wasteful activities. These NVAs are introduced as a list of waste and categorized as a “waste list.” The list helps stakeholders provide another layer of analysis for waste root causes in a construction system.

Waste is conceptualised in lean literature as a communication tool and unit of measurement. The first consideration of waste is to be conceptualised as an actionable language that facilitates discussion among stakeholders, where a storytelling approach describes the generated waste, the nature of this waste, and the consequences of this generated waste. This approach increases situational awareness among stakeholders who can collaboratively identify and address the root causes of production bottlenecks in their projects or organisations. Secondly, waste is a metric used to measure the root causes of inefficiency within a production system or organisation, and it provides insights into the key processes and operations that require further attention for improvement. This conception of waste also enables the stakeholders to recognise potential gains that can be realised through waste elimination initiatives (Bølviken et al., 2014). Thus, within a lean construction framework, waste elimination catalyses proactive learning, problem-solving, and continuous improvement rather than merely being a byproduct of production processes.

2.6.2. What are waste elimination factors imposed by lean construction?

The waste elimination measures provided by lean construction can be categorized into two distinct facets: social and technical, as shown in Table 2-5. The waste elimination concept is centralised in lean construction foundations operationalised in production planning and control. Due to waste elimination concepts and functions embedded within lean production planning and control, planners can provide more reliable plans and trades work within more stable workflows. The literature review revealed eight fundamental principles identified: (1) reducing cycle time, (2) minimising variability, (3) fostering continuous improvement, (4) enhancing transparency, (5) decreasing batch size, (6) minimising rework, (7) reducing inventories and (8) mitigating defects (Koskela, 2000; A. Santos, 1999). Table 2-5 pointed

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to the factors of LC for waste elimination based on lean principles in the Lean Foundations column. The second fold is streamlined from production planning and control functions; this study shortens the lean function to this role because it can be applied to various stages of Integrated Lean Project Delivery (design, supply, assembly, and use). The second aspect of the response stems from insights derived from production planning and control functions. Given its versatility in application across various stages of Integrated Lean Project Delivery (including design, supply, assembly, and utilisation), this study simplifies the lean function to this role.

Table 2-5–Lean construction factors of waste elimination

Measures	Lean Foundations	Production Planning & Control Functions	Stable and Reliable Production Plans
Social	• Respect People • Decide by consensus. • Extend the network of partners. • Capture the customer value. • Align internal and external clients.	• Feedback from downstream • Collaborative planning and control • Use Language/Action perspective. • Hand-off Management • Provide reliable promises. • Commitment planning	• Increase Situational awareness. • Feedback loops • Upstream understand downstream work • Measure commitment
Technical	• Simplify processes. • Use Reliable Technology • Reduce Cycle Time • Reduce batch size. • Increase Transparency • Standardise • Continuous Improvement	• Pull Planning • Work structuring. • Visualise material and information flow. • Pull Planning • Constraint Analysis • Interference Analysis • Alignment Analysis • Root Cause Analysis • Schedule buffers allocation • Control Metrics • Control Charts • Resources Allocation	• Product and flow visualisation • Production Stability • Continuous one-piece flow • People commitment • Variability Reduction • Workable backlogs • Quality Improvement • Control Actions • Workflow reliability metrics

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2.6.3. What are waste elimination factors imposed by lean construction (LC) and Building Information Modelling (BIM)?

Most collected documents used BIM as a parallel process with lean construction implementation regarding waste elimination based on LC-BIM. This assertion agrees with the results presented by Ratajczak et al. (2017). Regarding waste elimination measures offered by adding BIM to LC, both systems appeared to tackle the root causes of waste caused by fragmentation between process and product information (Dave & Sacks, 2020). However, the literature never quantified waste elimination, which appears somewhat necessary.

From a strategic point of view, few lean design studies have actively pursued implementing BIM standards (ISO, 2018) while executing BIM workflows in Lean construction projects. However, no correlation was determined between these standards and waste elimination. The extant literature failed to identify the impact of waste elimination practices on BIM standards. This gap would suggest future research agendas focusing on finding the potential waste elimination-based BIM standards currently not prioritised in the reviewed literature.

Again, the literature considered BIM's potential significant in streamlining LC principles, methods, techniques, and tools; therefore, many waste elimination measures were initiated to improve information flow, as shown in Figure 2-16. It is interesting to note consistent overlaps of 'simulation' and 'quantity-take-off' during production planning and control by streamlining reliable and real-time production Information to stakeholders that use LPS and LBMS. However, only developing LC-BIM integration during lean supply, planning, and control functions. For example, little research has been conducted to study the impact of LC-BIM on the "use" and "lean design" stages, which include renovation, retrofitting, expansion, and demolition (Elmaraghy et al., 2018). This assertion would suggest that the literature considered that most construction waste is caused by planning and control in the lean assembly stage and is rarely generated directly or indirectly during the lean design and supply stages. This perception is a denial acknowledged by (Cheng & Ma, 2013; Uusitalo et al., 2017), whose findings reveal that the BIM process contributes significantly to construction production planning and control reliability.

The literature has attempted to develop software that harnesses BIM functionalities to automate LPS implementation (Dave, 2013; Heigermoser et al., 2019; Sacks et al., 2010; Schimanski et al., 2021). These systems share some characteristics: 1) visualising the process and product information; 2) providing digital kanban cards; 3) digitising constraint analysis workflow and managing constraints data;

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4) enabling communication between design management, project management, site management, and crews; 5) monitor project, process and operation progress, 6) enable the production metrics to highlight wastes. Such software advances the planning functionalities offered by commercial BIM systems by increasing the planning details from master schedules only to medium- and short-term planning. Additionally, they enable the feedback from labourers at the coal face when data entry forms are available for each planned task. Moreover, tracking technologies such as IoT (Dave et al., 2016), GPS, beacons, and autonomous drones (Lin & Golparvar-Fard, 2021) enable automatic information capture to monitor production progress and material supply and logistics statuses. Such technologies would be fundamental to realise initiatives such as artificial intelligence, Big Data, Digital twins for construction (DTC), and Industry 4.0 (McHugh et al., 2022).

Based on the above discussion, this chapter presents a conceptual framework (Figure 2-16) that assembles production planning and control functions based on lean construction and the existing functionalities of BIM to streamline waste elimination measures, which eventually provide more stable and reliable production plans. The links between concepts in the presented framework, Figure 2-17, will be a basis for hypothesis generation in the following chapter (Chapter 5).

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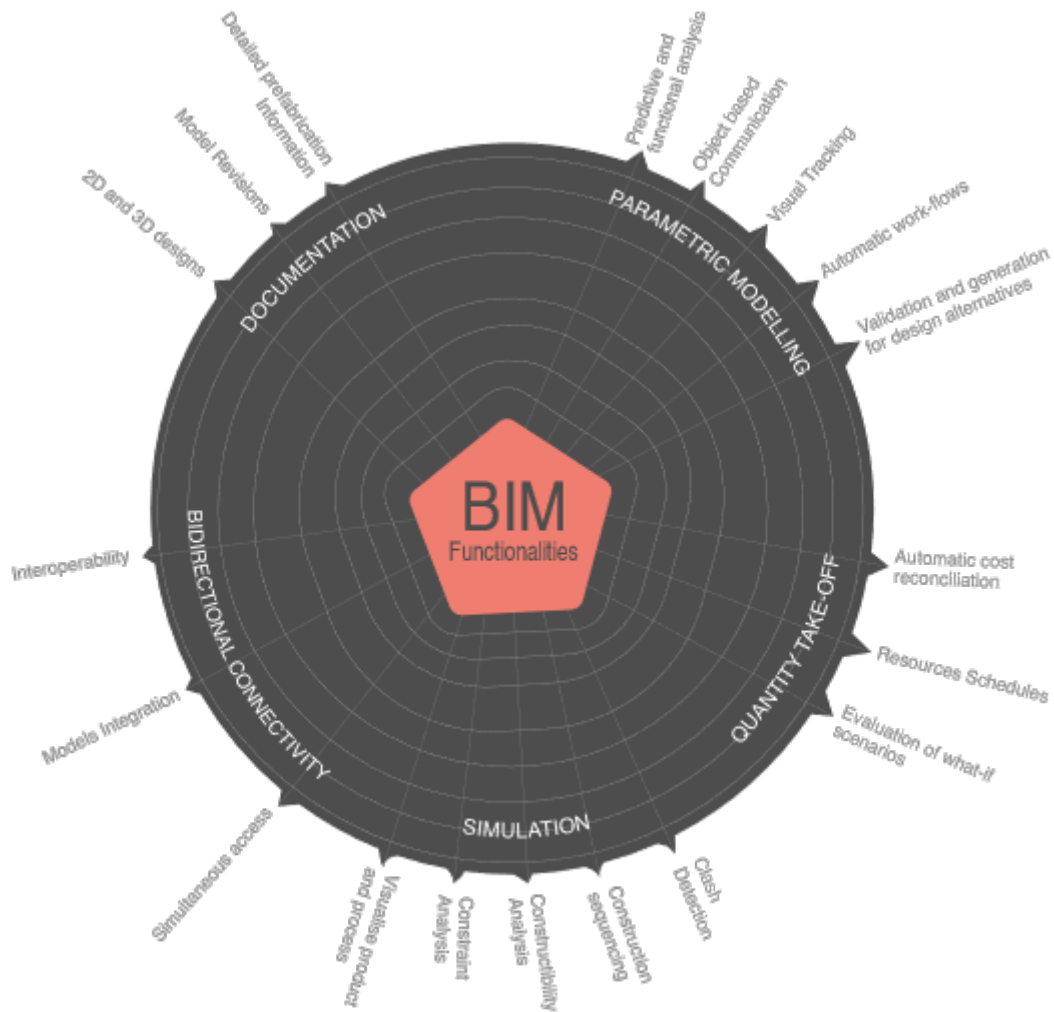


Figure 2-16– Critical factors of BIM functionalities supporting lean construction functions.

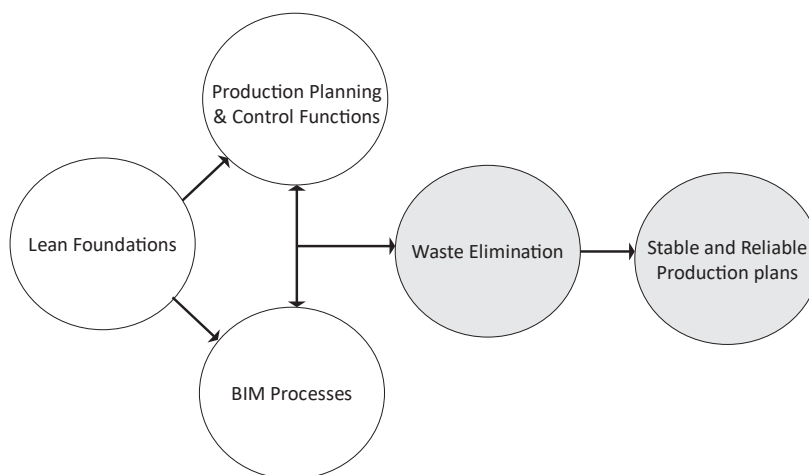


Figure 2-17-Generic conceptual Framework for waste elimination model based on Lean construction and BIM.

2.7. Conclusions

This chapter presents an in-depth literature review based on the systematic literature review methodology according to (Tranfield et al., 2003). The review objective was to understand: i) how lean construction (LC) conceptualises waste and ii) what waste elimination factors are imposed by LC and Building Information Modelling (BIM). Based on predefined exclusion and inclusion criteria, the number of records has been filtered from 406 to 54 relevant documents. A time analysis was presented to illustrate the accumulation of waste elimination knowledge based on LC and BIM between 1992-2021. This analysis shows that the emergence of the waste elimination concept based on LC has been evolving since 1992, while an integrative approach of LC-BIM was first reported in 2008. The analysis also indicates a small quantity of theoretical and review research compared to empirical research. This assessment shows a lack of theoretical foundations for LC-BIM topics, and even if it exists, waste elimination was implicitly discussed or separately analysed.

Waste is a high-level and context-specific concept hindering production performance and negatively impacting social, economic, and environmental dimensions. The theoretical papers discussed the idea of construction waste in terms of nature, conceptualisation, taxonomies, and propagation and reviewed cause-effect relationships between different types of waste. The lean construction community seeks a holistic understanding of the root causes of production waste and the consequences on the overall supply chain. The nature of production waste inherits the characteristics of the construction processes in terms of dependencies between tasks. (Formoso et al., 2015) It shows that the pattern of waste propagation can be mapped into networks of waste cycles, typically initiated by failures in construction management functions (production planning and control, product design, site layout planning, previous stages, and quality management). The taxonomy of construction waste has been adopted from manufacturing research (i.e., Ohno's list of waste (Ohno, 1988)). This list has been transferred into practice without reflection on the construction peculiarities. Hence, a context-specific taxonomy is needed for the construction, as Formoso et al. (2020) suggested. Bølviken & Koskela (2016) reported that the concept of waste had been ignored in the construction management research, and the practice lowers the importance of waste elimination in their agenda. This assertion shows that future research should focus on developing new theories based on production theories to understand and capture the characteristics of production waste in the construction context.

However, the consensus on the dominance of Making Do and its enormous impact not only generates production waste (NVA) but can also hold responsible behaviour for hindering the overall

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project performance. The current waste taxonomies do not directly address the Making Do waste generation and its effect on the construction industry. For example, Formoso et al. (2020) identify Making Do as one of the types of production waste that occurs at the beginning or continuation of a task with incomplete resources, resulting in reactive decisions such as 'firefighting' or 'low-fruit gripping,' they do not describe its peculiarities in detail. While these taxonomical frameworks help conceptualize construction waste, such an approach is insufficient in analysing Making Do. A dedicated taxonomy for Making Do waste could consider factors like inaccurate task planning of the project schedule, ineffective communication between trades, unpredictable arrival of materials, and improper control of the resources. In order to gain insight and progress in the comprehension of Making Do, researchers can ground it in a particular taxonomy, measure its duration and the extent of its influence, and create effective strategies for its reduction.

The empirical literature themes have been classified following the proposed model of Integrated Lean Project Delivery (ILPD) (Ballard & Howell, 2003). The thematic analysis shows that waste elimination is a primary part of lean construction projects from the early stages, which should be defined in relational contracts as project purpose in the project definition stage. However, the existing contractual structure (e.g., Design-Bid-Build, Integrated Project Delivery (IPD)) does not include implicit clauses for waste elimination in its templates. This gap can hinder stakeholders' commitment to waste elimination due to the absence of regulatory measures (Matthews et al., 2000; Vilasini et al., 2014). Concerning the sustainability dimensions, the literature reported "improving sustainable performance" as an explicit objective within some lean construction projects. The consensus by using Value Stream Mapping (VSM) shows that production waste elimination is not only reducing environmental waste (such as material waste, landfills, gas emission, energy consumption, and wastewater) (Kim & Bae, 2010; Rosenbaum et al., 2014). Nevertheless, social benefits can also be reaped by reducing the likelihood of accidents and injuries on-site or in construction factories (Gambatese et al., 2017). The economic impacts of waste elimination are presented in terms of reducing operation costs and shortening the lead time of overall project delivery, which are objectives of any lean initiative (Vrijhoef, 2020).

The lean design has an essential role in generating information for fabrication, logistics, assembly, and facility use, but the literature lacks approaches that study the effect of LC-BIM on the whole supply chain. The role of BIM is significant if lean construction is to be continued as the dominant construction management method in the future; the current state of queue shows that the only possible way to automate lean systems is by melting the boundaries with BIM. Thus, the parallel use of both concepts is not enough. A typical integration between LC-BIM exists in production planning and control systems

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(i.e., Last Planner System (LPS) and Location-Based-Management-System (LBMS)). LPS and LBMS have complementary functions in creating reliable and stable plans together. The potential of harmonised use of both systems has been revealed and applied in previous studies (Dave et al., 2016; Seppänen et al., 2010, 2015), which show that both systems are highly correlated; for example, LBMS become deficient without effective social communication for information, on the other hand, LPS requires more metrics than PPC to measure the quality of the construction flow which LBMS offers. Both systems rely on intensive production information in terms of quantity, duration, and task definition, and BIM can provide that, which supports production planning and control with the necessary information when needed.

A more critical waste elimination-focused research agenda is currently required to investigate the integration mechanisms of the BIM and LC concepts across the supply chain. Given that the diffusion of BIM and LC have been studied since 2008, it is possibly surprising that so few have investigated their combined implementation for waste elimination purposes. A comprehensive understanding of this combined BIM and LC requires considerations of the processes, technology, and diffusion mechanisms to inform practitioners and policymakers of the industry. To overcome the limitations of this study in terms of covering records collected from databases other than Scopus, databases such as Web of Science (WOS), Google Scholar, and EBSCO literature collection and review can be implemented in the future.

3. Research Methodology

This chapter aims to elucidate and justify the selection of the research methodology. Initially, it examines the existing research methodologies in construction management and selects an appropriate research methodology that aligns with the collected data and research objectives. Subsequently, it delves into a comprehensive discourse on system modelling and simulation methods employed throughout this thesis: The main theories and compartments of System Dynamic Modelling (SDM) are reviewed and discussed. That includes a detailed exploration of their inherent characteristics, underlying processes, and potential limitations. Finally, the chapter culminates with a methodological framework that outlines the approaches employed to verify and validate the constructed model.

3.1. Introduction

In pursuing a comprehensive framework underpinned by lean policies centred on waste reduction and value generation, gaining a profound comprehension of the intricate dynamics of information dissemination and individual interactions with elaborated systems becomes imperative. In this context, deploying system modelling and simulation methodologies emerges as a recommended avenue for enhancing the grasp of complicated and dynamic quandaries employing abstracted representations of the real-world *milieu*. These methodologies encompass and integrate principles stemming from systems thinking theories, discrete event simulation (DES), dynamic modelling (SDM), and multi-agent simulation (MAS). Each of these methodologies serves distinct purposes across varying tiers of abstraction and analysis. While utilising a solitary or amalgamated simulation approach can augment the comprehension of production systems and the pertinent managerial policies, such deliberations lie beyond the scope of the present thesis.

Adopting the SDM approach can potentially furnish a holistic panorama of waste generation phenomena at diverse analytical levels, thereby facilitating stakeholders in refining their insight into production processes and extant policies. This approach aids in optimising resource allocation, exploring hypothetical scenarios, and reinforcing communication and collaboration, ultimately culminating in the refinement of informed decision-making. Under its capability to examine complex social systems (CSS) and illuminate strategies for waste mitigation, SDM emerges as an indispensable tool. Hence, this study advances the deployment of System Dynamics Modelling (SDM) to delve into the dynamics of systems and the efficacy of waste reduction strategies engendered through the amalgamation of planning and control functions, namely the Last Planner System (LPS), the Location Based Management System (LBMS) and Building Information Modelling (BIM).

The primary objective of this chapter is to provide researchers and policymakers with the implementation of SDM to assess the impact of Lean Construction (LC) instruments (LBMS and LPS augmented by BIM) in their respective organisations with the aim of curtailing waste impact. This objective entails micro-mapping objects and spaces through dynamic simulation modelling, encompassing interdisciplinary dimensions spanning social, economic, environmental, and production realms.

The organisation of this chapter unfolds across four pivotal sections. In the first section, an overview of prevalent research methodologies in construction management research is presented, substantiating the chosen research approach adopted throughout the trajectory of this thesis. The second section

3. Research Methodology

presents an overview of data research analysis methods. The third section examines exploratory and confirmatory factor analysis methods to discover the underlying structure of Making Do waste, Last Planner System, and BIM variables. Subsequently, the fourth section examines the nuances of system modelling and simulation approaches, with a more comprehensive investigation into the tenets of system dynamic modelling. This chapter serves to rationalise the rationale underlying the employment of SDM within the purview of this thesis. The concluding two sections proffer a thorough chapter analysis, culminating in overarching conclusions concerning the research methodology.

3.2. Methodologies to Access the Construction Management Research

3.2.1. Philosophical worldviews

How we see the world determines our understanding of the research problem and decides the research methods and approaches to tackle this problem. This world has four distinct philosophical views: positivism, constructivism, critical realism, and pragmatism (Creswell and Creswell 2017).

Positivism

The positivist stance is deeply rooted in the epistemological philosophy that contends with the absence of a singular, absolute truth concerning reality. Instead, it advocates validating theories through empirical observations (numerical data). The veracity of this perspective is established through a continuous cycle of observations or the replication of experiments. Within this framework, positivists engage in systematic investigations to ascertain causality, thus translating the mechanisms that bring about desired outcomes. The core of this approach revolves around explicating the regularities exhibited by variables, culminating in the confirmation, enhancement, or refusal of extant theories. In the realm of positivism, the role of the researcher assumes an objective stance, dissociated from personal biases or influences. In this context, the researcher typically maintains a detached position vis-à-vis the observations. Notably, the research orientation that aligns with post-positivism predominantly adheres to quantitative research methodologies, characterised by their numerical and measurable attributes. Traditional empirical research undertakings are underpinned by operationalism, which involves dissecting complex concepts into distinct and quantifiable components. Furthermore, assessing measurement validity and reliability remains integral to conventional empirical research processes, ensuring the robustness and consistency of the generated results (Johnson and Duberley, 2000).

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Positivism proponents within construction management studies frequently use quantitative methods: questionnaires, regression analysis, structural equation modelling, and experimental designs (Akinade, 2017).

Constructivism or Interpretivism

The constructivist perspective sharply contrasts with positivism, rejecting claims of objectivity and reductionism. Instead, it embraces socially constructed knowledge rooted in reasoned hypotheses and emotions. Constructivists assert that knowledge emerges through active engagement, interpreting nuanced meanings in complex contexts (Mir & Watson, 2001). This approach unveils the significance of experiences within specific frameworks. Data collection in constructivism leans towards qualitative methods. Researchers interact subjectively, potentially shaping interpretations with personal experiences. In construction management, constructivist proponents often favour qualitative techniques like interviews, textual analysis, direct observations, focused group discussion, and experimental designs, facilitating the exploration of intricate phenomena and multifaceted contexts.

Critical realism

Critical realism combines positivist and constructivist approaches, addressing positivism's limitations while maintaining objectivity. It integrates constructivist elements (Guba and Lincoln, 1994), upholding objectivity in mediated data collection. Critical realists stress replicable findings across diverse samples, populations, and methods (Mir and Watson, 2001). Valid epistemologically, ideographic studies in this framework clarify structures and mechanisms underpinning observed phenomena. Like constructivism, critical realism interprets the intricate world, acknowledging complex organisational structures influenced by observed phenomena. Under this approach, researchers may merge interviews, questionnaires, experimental research, structural equation modelling, or system dynamics. Its popularity lies in offering research flexibility in method selection (Fellows & Liu, 2015, p. 74).

Pragmatism

Like critical realism, the pragmatic view bridges constructivism and post-positivism, focusing on actions and consequences. It blends quantitative and qualitative methods, fostering reciprocal knowledge-theory interaction. Pragmatism acknowledges resistance in human actions independent of observation. Epistemic relativism guides this perspective, intertwining situational and inquirer aspects. Inquiry intent shapes perception. The goal is to create intelligible models of human experience that aid experiential organisation. Knowledge is viable interpretations rooted in expertise, ready for intentional action—embracing generic models and propositions.

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Paradigm Evaluation and Adoption for the Study

The preceding assessment of various research paradigms has revealed notable limitations within the positivist and constructivist frameworks. Specifically, the former requires an immersive grasp of the researcher's cognitive processes, extending beyond predictive and control-oriented perspectives. Moreover, an inherent need to comprehend the planner's cognitive landscape surfaces when reconstructing this realm, thereby necessitating a deeper comprehension of the underlying knowledge structures governing decision-making processes. In light of these considerations, an inclination towards embracing constructivist paradigms becomes evident, particularly in formulating strategies for circumventing challenges.

Nonetheless, the adoption of constructivism has its attendant challenges, as previously expounded. Given the robustness and adaptability intrinsic to the critical realism paradigm, this study underscores its significance. Consequently, the research embraces a critical realism philosophical stance, centred on efficacious applications that facilitate a comprehensive problem elucidation while measuring the artefacts' impact in resolving the issue. This orientation equips the researcher with the necessary tools and resources to thoroughly engage with the research difficulties, fostering a focused problem-solving approach. Embracing a holistic framework, the researcher extracts knowledge from multifaceted avenues to address the research conundrum, as delineated by (Fellows & Liu 2015, p. 161).

As evidenced in Table 3-1, selecting a philosophical standpoint plays a pivotal role in determining the research approach, shaping the data collection, and analysing methods pursued to achieve research objectives or resolve research inquiries. This comparative overview facilitates a comprehensive examination. Employing a blend of research approaches holds distinct advantages, mainly because organisational decisions are typically a culmination of inputs from diverse individuals, each hailing from different backgrounds, concealing varying interests, knowledge, and perspectives concerning information's credibility (Patton, 1997). While some may endorse the reliability of positivist studies, others might advocate for the constructivist viewpoint, valuing its potential to offer innovative knowledge representations. Such contrasting perceptions can lead to conflicts of interest regarding using quantitative or qualitative information for decision-making.

Enter critical realism, designed to circumvent such conflicts by providing a mixed methods worldview. It emerges as a pragmatic solution, poised to tackle research's practical challenges and uncertainties. Critical realism effectively enables researchers to harness the advantages of seemingly conflicting philosophical perspectives, all in pursuit of contributing knowledge toward resolving specific

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contextual problems. The limitations inherent in adhering to a singular philosophical standpoint are well-established and widely acknowledged within the realm of research. Critical realism, in essence, addresses these inefficiencies by facilitating the judicious incorporation of beneficial strategies from both paradigms, thereby optimising research outcomes.

Table 3-1 – Construction management worldviews adapted from (Creswell & Creswell, 2017; Fellows & Liu, 2015)

Philosophical worldviews	Critical Realism		Constructivism	Positivism		Pragmatic
Ontology	Real, reality	Layered	Socially constructed reality	Single reality	objective	Axiology
Epistemology	Knowledge extended from human interpretation	from	Co-constructed knowledge	Knowledge derived from observation	is from	Actionable and practical knowledge
Axiology	Values inform understanding	inform	Values and context shape knowledge	Values separate research	are from	Values linked to consequences
Reasoning	Abductive		Inductive	Deductive		Mixed (Deductive and Inductive)
Type of research design	Mixed, Explanatory, Interpretive	often	Explanatory Descriptive	Exploratory Interpretive		Mixed methods
Nature of observed reality	Essential, impacted observation perception	but by or	Constructed by human experience	Directly observable		Dual reality constructed from social impacts and observations or perception
Role of Manager	The reactor may initiate action		Actor, generator of context and action	Information processor		Active and projective
Nature of strategic choice	Influenced by the underlying structure		Ideological actions of sub-organisational interest groups	A boundedly rational response to contingencies		Top-down And down-up
Organisational identity	Integrated, multiple	often	Multiple, Fragmented	Overt (open to view), Singular		Integrated organisations support collaboration Two ways communication between observations and theories
Theories of measurements	Acknowledges complexity		Context is the primary key to perspective	Replications as a key to accuracy		

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Research approach	Mixed, Qualitative	often Qualitative	Quantitative	Mixed methods
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This research will mix constructivism and positivism ontologies, and the former seeks to construct the knowledge based on practitioners' views on construction projects. The latter directly observes the making-do phenomena through collected data from the construction projects. Both worldviews decide the mixed research approach, and the qualitative research approach provides the context of the significant perspective. The role of the researcher can be objective in terms of using closed-ended questions to the research subjects. Alternatively, open-ended questions that the role of the researcher is an actor. These worldviews and their followed research approach are selected because of the available data collected.

3.2.2. Research Design

There are several strategies for conducting research, and the literature abounds with contradictory claims regarding the right approach to achieve specific research objectives or problems (Creswell and Creswell, 2017). As such, considerable effort is required to choose the appropriate research approach and data collection methods in response to the research questions. This investigation enables the researcher to plan while properly considering the research paradigm, strategies, and techniques. Three research approaches are commonly used in construction management research: quantitative, qualitative, and mixed methods.

Quantitative methods

Engaging in quantitative research entails the meticulous measurement of data through suitable scales. Two fundamental questions guide this process: What aspects should be measured, and how should these measurements be executed? (Fellows & Liu, 2015). The choice of measurement scale is paramount, ensuring ease of data collection, accuracy, and the validation of subsequent analyses. In an ideal quantitative approach, the researcher's influence on the collected data is minimised to uphold objectivity and mitigate the potential impact of personal beliefs.

Quantitative methods adopt an empirical stance to measure data about key variables using appropriate scales. Building on existing findings to enable replication, researchers formulate inquiries. Predominantly following a deductive research paradigm, quantitative methods emphasise hypothesis and theory testing alongside exploring variable relationships. It commences with a hypothesis or conceptual model construction grounded in existing literature and theories; subsequent stages

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encompass data collection and analysis to substantiate these initial constructs. This approach resonates with the positivist philosophical standpoint (Fellows & Liu, 2015).

Efficiency in data collection and proficiency with recognised quantitative data analysis techniques constitute the primary strengths of quantitative research. Noteworthy examples include experimental designs and survey research. Experimental design assesses the impact of independent variables on one or more dependent variables. In this context, the dependent variable represents the measured response. Between-subjects designs involve randomly assigning subjects to experimental conditions, enabling data collection across various groups.

On the other hand, survey research gauges trends, attitudes, or consensus within a population sample to generalise findings to a broader context. It facilitates the extension of conclusions from a sample to the entire population. Survey research predominantly employs questionnaires as data collection tools, encompassing closed-ended and open-ended queries. While self-administered and posted questionnaires are standard, the popularity of web-based questionnaires, utilising platforms like SurveyMonkey, QuestionPro, Google Surveys, and Microsoft Forms, has grown. Leveraging web-based questionnaires enhances best practices, encourages participation, reduces potential errors, and streamlines data processing and analysis.

Qualitative methods

Qualitative research predominantly adopts an inductive approach centred around theory generation. Within this research framework, textual analysis is a common practice. The research process initiates with data collection and subsequent analysis to discern patterns, culminating in constructing a theoretical framework. Qualitative research offers a notable advantage by delving deeply into the phenomena under investigation, although it often demands a considerable time investment. Qualitative research encompasses diverse methodologies, including ethnography, grounded theory, phenomenology, and case study.

Qualitative research methods find their primary utility in comprehending the underlying causes, principles, and behaviours associated with a given problem or issue, as expressed by participants (Fellows and Liu, 2015). The researcher's role includes determining variables and the corresponding measurement methodology. For instance, phenomenological research entails an inquiry design to elucidate individuals' experiences of a phenomenon, frequently accomplished through interviews (Giorgi, 2009). Grounded theory is a research strategy in which a theory of process or behaviour is devised and grounded in the participants' views (Creswell & Creswell, 2017).

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On the other hand, case studies facilitate an in-depth examination of a case, process, event, or individual within the bounds of specific temporal and activity parameters, utilising an array of data collection techniques (Yin, 2018). The informing case studies will be used in this thesis as a method of research that includes a detailed examination of Making-Do waste as a single instance to conclude broader insights and theories while understanding complex phenomena from different perspectives (F. Chen et al., 2020; Dixon-Woods et al., 2007; Ickis & Omazić, 2013).

Mixed methods

The mixed methods approach harmonises quantitative and qualitative data, addressing the limitations of individual methods and offering more profound insights into the research question. While terms like multi-methods, integrated methods, and quantitative and qualitative methods are used, "mixed methods" is the most prevalent designation (Creswell & Creswell, 2017). This approach leverages triangulation, wherein diverse data sources are scrutinised to establish research themes. In line with Creswell's categorisation based on the sequence of method application, mixed methods exhibit three primary types: 1) convergent parallel mixed methods, involving simultaneous collection and comparison of qualitative and quantitative data; 2) explanatory sequential mixed methods, commencing with quantitative data collection and analysis before proceeding to qualitative data collection and analysis; and 3) exploratory sequential mixed methods, initiating with qualitative data collection and analysis, followed by corresponding quantitative phases. These typologies provide structure to data integration and offer researchers a framework for conducting comprehensive mixed methods studies.

3.3. Data analysis methods

3.3.1. Pareto (80/20) rule

A Pareto chart combines bars and a line graph, with individual values arranged in descending order on the bars and the cumulative total represented by the line. The chart is named after the Pareto principle, which, in turn, is derived from the economist Vilfredo Pareto. The primary objective of using a Pareto chart is to highlight the most significant factors. It is commonly utilised in quality management as a tool for quality control. The chart proves helpful in identifying the most probable causes of defects in products and processes, aiding in focused problem-solving and decision-making within various industries.

3.3.2. Factor Analysis

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Factor analysis is a statistical method for discovering a rotated subset of principal components that, instead of the original variables, reduce the amount of noise in the data while retaining the information that stands for the actual variables in the "Multivariate Data Analysis" (Hair et al., 2019). It is mainly used in data reduction and dimensionality reduction, where the objective is to decrease the number of variables into fewer factors, subject to the best preservation of the original variability. Factor analysis intends to discover the underlying structure in the data using its ability to recognise common patterns among the observed variables. These unknown factors are the basis that encompasses the aspects of the subject that are not directly measured but are perceived through the gathered variables. The factor analysis procedure differs in how the factors have been extracted from the correlation matrix of the observed variables with the rotated factors that yield a more straightforward and easier-to-interpret solution. The resulting factors shed light on the interconnections between the observed variables and the main factors aiding in understanding the outcomes. In summary, exploratory factor analysis is vital for revealing the distinctive content of multivariate sets and determining the latent factors that produce the complex pattern of associations in the data set.

3.3.3. Chi-Square Association test

The chi-square test uses a contingency table to evaluate hypotheses for statistical analyses, especially when the sample size of the collected data is large (Field, 2005; Hastie et al., 2009). This test mainly examines the relation between two categorical variables in a cross-tabulation setting. These cross-tabulations classify the data into two discrete or groupings, implying two independent variables in the dataset. The rank of the table refers to the categories of the first variable, while the column indicates the category of the second variable; each variable must have more than one category or factor. Any cell in the chi-square or contingency table sums up the number of occurrences that fall within a particular combination of the categories, making it easier to understand the interrelation between variables. The chi-square test encompasses two primary types of statistics: Pearson's and Likelihood ratio chi-squares. The formula for each is stated below.

In Equation 3.1, p_i represents the summation of all probabilities p_i , across all categories i from 1 to r . In a random sample of n observations from a population, these observations are divided into r mutually exclusive classes, each with corresponding observed numbers x_i (for $i = 1, 2, \dots, r$). The null hypothesis states the probability p_i that an observation belongs to the i th class. χ^2 represents the Chi-square (χ^2) statistic, a measure of how observed data deviate from expected data. That tests the interdependence of two categorical variables and the goodness-of-fit between observed and expected frequencies. For each cell in the contingency table, χ^2 calculates the ratio of the square of observed frequency (O_{ij}) to the

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expected frequency (E_{ij}). The result is the χ^2 statistic, and in order to decide whether the differences observed are statistically significant or not, it is compared with the critical value from the Chi-Square distribution with the relevant degrees of freedom.

$$\sum_{i=1}^r p_i = 1 \quad \text{Equation 3.1}$$

$$\chi^2 = \sum_{i=1}^r E_{ij} = \sum_{j=1}^c \frac{O_{ij}^2}{E_{ij}} - n \quad \text{Equation 3.2}$$

$$\text{where } E_{ij} = \frac{(\text{total row}_i) \times (\text{total column}_j)}{\text{total number of observations}} \quad \text{Equation 3.3}$$

Likelihood-ratio chi-square statistic represents the ratio between observed and expected frequencies in the association table as expressed in Equation 3.5

$$G^2 = 2 \sum_{i=1}^r \sum_{j=1}^c O_{ij} \ln \left(\frac{O_{ij}}{E_{ij}} \right) \quad \text{Equation 3.4}$$

Where O_{ij} is referred to the observed value for frequency in the cell (i,j), E_{ij} is the expected frequency value for cell (i,j).

A contingency table's degree of freedom (DF) is the number of parameters that can vary independently in a statistical computation. DF is the number of cells in the association table that can be changed freely once the row and column totals are fixed. Equation 3.6 shows the formula of DF, where R is the number of rows and C is the number of columns. DF is essential when using χ^2 statistics because DF helps determine the critical value of the Chi-Square distribution, allowing the researcher to compare calculated Chi-Square values to decide whether to reject the null hypothesis.

$$DF = (R - 1) \times (C - 1) \quad \text{Equation 3.6}$$

3.3.4. Linear Regression Analysis

Linear Regression Analysis (LRA) is a statistical modelling technique that examines causal relationships within predetermined datasets that are linear in the parameters. It formulates linear equations, specifically the best-fit line (commonly known as the least square line), to explicate the associations between predictor and dependent variables. LRA proves invaluable for researchers in predicting and

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forecasting the behaviour of modelled data, exhibiting convergence with methodologies inherent to machine learning. The Linear Regression model serves the purpose of estimating parameters involving unknown variables, denoted as β for parameters; predictors, denoted as X_i , dependent variables represented as Y_i and errors signified by e_i . The resultant linear formula for the regression function Y_i is expressed as follows:

$$Y_i = f(X_i + \beta) + e_i \quad \text{Equation 3.7}$$

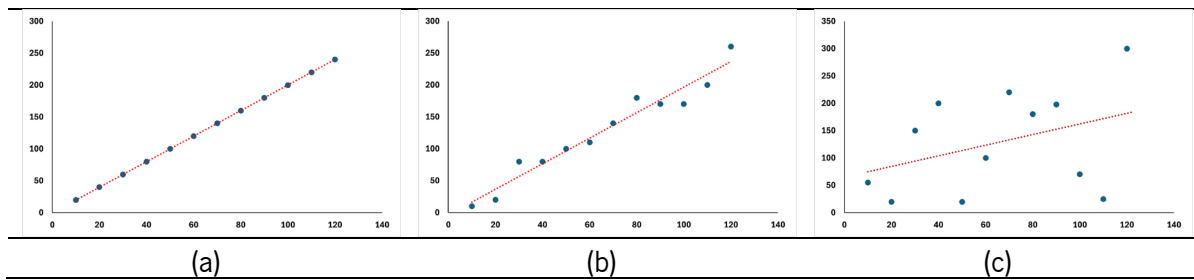
The resulting regression models should be tested for fitness, and several statistical indicators describe the fitness of regression models, such as standard deviation (S), R^2 , adjusted R^2 , and Durbin-Watson statistic.

S stands for the standard deviation of the residuals that measures the distance between the data values and the fitted values provided by the regression model. This statistic is measured in the same units as the dependent variable (response). A lower value of S indicates a better fit for the model to describe the data. However, a lower S value alone does not guarantee the validity of the underlying model assumptions. It is essential to examine residual plots to verify potential violations of assumptions, thereby ensuring the model's reliability.

R^2 (R-squared), or the coefficient of determination, represents the proportion of variance in the dependent variable accounted for by the independent variables in the model. It is calculated as one minus the ratio of the residual sum of squares (representing the unexplained variation) to the total sum of squares (representing the total variation within the data). R-sq is a crucial metric for assessing the goodness of fit of the regression model, with higher values indicating a more significant proportion of explained variance and a better fit to the data. The R-sq value ranges between 0% and 100%, where 0% indicates that the model explains none of the variations, as shown in Figure 3-1 (c), 50% indicates that the model explains 50% of the variation, as in Figure 3-1 (b) and 100% indicates the model explains all the variation Figure 3-1 (a).

$$R^2 = 1 - \frac{SSR}{SST} = 1 - \frac{\text{Sum Squared Regression}}{\text{Sum of total Squares}} = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}$$

Figure 3-1– R squared values representing the goodness of regression line fit



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The Durbin-Watson statistic tests first-order autocorrelation in time series data without lagged independent variables ranging from zero to four. A value close to 2 shows no autocorrelation, while an appropriate range is about 1.50 to 2.50. Values below 1.50 indicate positive autocorrelation; values above 2.50 indicate negative autocorrelation. However, the Durbin-Watson statistic becomes unreliable in models that contain lagged variables. High autocorrelation, in series with seasonal solid patterns, suggests that ordinary least squares regression may not be the most accurate method to use when forecasting.

$$DW = \frac{\sum_{i=2}^r (\hat{\varepsilon}_t - \hat{\varepsilon}_{t-1})^2}{\sum_{i=1}^r \hat{\varepsilon}_t^2}$$

3.3.5. PLS-SEM Statistical Technique

The primary virtue of structural analysis lies in its ability to propound, explore, and implement scientific discoveries, making it an inevitable passage for contemporary researchers of either natural or social sciences. The Partial Least Squares Structural Equation Modelling (PLS-SEM) was a second-generation approach among the multivariate analysis methodologies. On the other hand, Covariance-Based Structural Equation Modelling (CB-SEM) prevailed in social science literature till around 2010, whereas CB-SEM was at the apex. Therefore, researchers should be aware of these historical developments to embrace new possibilities. At the same time, PLS-SEM, which is above the CB-SEM in popularity nowadays, has experienced a significant spike in the number of publications made in many disciplines such as marketing, management, information management systems, accounting, strategic management (Hair et al., 2019), construction management (Wang et al., 2024) and many others.

Within data analysis, univariate analysis involves studying a single variable to characterise its distribution with measures of central tendency and dispersion through graphical representation. This kind of approach of bivariate analysis can be taken to the next level by examining the relations between two different variables (or dependent and independent variables). It is done to find the patterns and associations in the data. Here, correlation analysis and regression can be utilised. Next, multivariate analysis deals with relationships among various multi-dimensional variables and uses a diverse set of statistical techniques, e.g., factor analysis, cluster analysis, and logistic regression, to discover unknown structures and intricate patterns within the data. This integrative approach allows researchers to tune into the complexities of interrelationships and the interactions among numerous variables, thus opening an opportunity for a more detailed comprehension of the phenomena (Hair et al., 2019).

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These multivariate statistical methods are often referred to as first-generation methods (Fornell, 1982) and can be categorised into two main types: conducting exploratory and confirmation studies. The confirmatory approach evaluates the theories developed and accepted a priori via henceforth known methods. Different attachment methods consist of logistic regression, multiple regression, analysis of variance, and confirmatory factor analysis. While prediction techniques aim to forecast existing or future patterns, the primary role of exploratory methods is to gain insights into the data when little or no previous knowledge is available. The exploratory methods include K-means clustering, multi-dimensional scaling, and exploratory factor analysis.

Regarding the choice of software, one has several options for implementing partial least squares structural equation modelling (PLS-SEM) and covariance-based structural equation modelling (CB-SEM). Regarding PLS-SEM, PLS-Graph by (Chin et al., 2003) is the mainly used option, and SmartPLS (Ringle et al., 2005) is also a favourite. Besides that, R and semPLS by Monecke and Leisch (2012) are also considered. While CB-SEM can be carried out using programs such as LISREL, AMOS, CALIS, EQS, and SEPATH, it comes with some constraints like measurement error, sample size, and unobservable errors.

The SEM procedure:

- Specify the measurement model: this step provides a rigorous analysis of the fitness of data with the modelled variables. Table 3-2 summarises the model indices and their acceptable values. As a composite of CMIN/df, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Residual (RMSEA), and Standardized Root Mean Square Residual (SRMR), these model-fit indices are commonly used for the overall evaluation of the model. Some calculated statistics significantly differed from the established below-standard value defined in previous research (Bagozzi & Yi, 1988; Bentler, 1990; Hu & Bentler, 1998; Schumacker & Lomax, 2004).

Table 3-2 – Model fitness measures

Fit indices	Threshold	Source
Probability level	Insignificant	(Bagozzi & Yi, 1988)
CMIN/DF	Between 1 and 3	(Schumacker & Lomax, 2004; Ullman & Bentler, 2012)
CFI	>0.95	(Bentler, 1990)

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TLI	>0.08	
SRMR	<0.08	(Hu & Bentler, 1998)

- Identify the Structural model: a structural model shows the expected relationships between the constructs (also called unmeasured or latent variables) and, in some cases, between the variables (also called observed variables) that serve as the measurement components of the constructs. The structural model describes the relationship between the variables, including their intermediate and direct relationships, and is often represented through a path diagram. This thesis applies two types of path analysis: mediation analysis and moderation analysis, as illustrated in Figure 3-2.

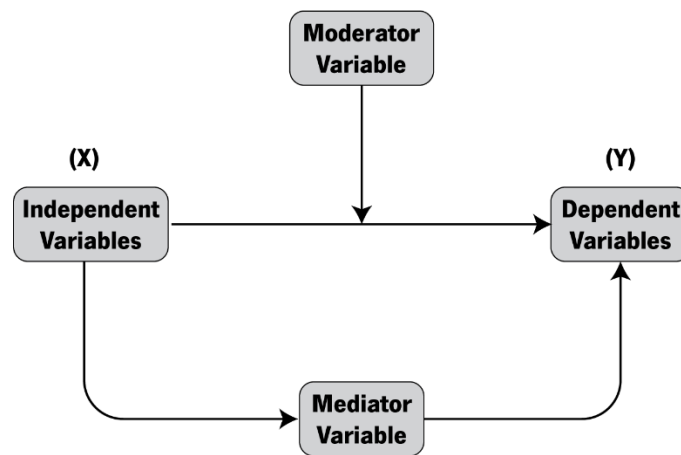


Figure 3-2 – Mediation analysis and Moderation analysis.

- Mediation analysis examines whether the effect of an independent variable (X) on a dependent variable (Y) is transmitted through a third variable known as the mediator. It explains how one variable affects another, including paths from X to the mediator, mediator to Y, and X to Y, and direct effect ($a*b$) (Baron & Kenny, 1986). The analysis involves the significance of the indirect effect ($a*b$) and often uses methods such as the Sobel test or bootstrapping for the significance of testing (Hayes, 2013).
- Moderation analysis examines whether the effect of an independent variable (X) on a dependent variable (Y) is moderated through a third variable known as the moderator. It defines the conditions of the relation between two variables changes, and this consists of the main effect of X and Moderator and the interaction effect of $X* \text{Moderator}$ on Y. Statistical analysis is typically used to analyse the significance of the interaction of the term ($X* \text{Moderator}$) whereby an assessment of its significance is usually carried out; sometimes simple slopes analysis is used for explaining this interaction (Baron & Kenny, 1986).

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3.4. Exploratory and Confirmatory Factor Analysis

This thesis employs Exploratory Factor Analysis (EPA) and Confirmatory Factor Analysis (CFA) to discover the underlying structure of LPS and BIM variables. Table 3-3 summarises the distinction between the two techniques. EPA is often used at earlier stages of the research when no priori hypotheses are available about the relationships between variables and factors; the data drive the procedure and investigate the underlying factor structure by identifying the number of factors and loadings of observed variables without any priori structure (Leandre R. & Duane T., 2011). EPA often utilises factor rotation to achieve a more straightforward and interpretable structure of factors. The CFA is often used to confirm the results of EPA by ensuring that each factor loads exclusively onto one construct; it increases the clarity and precision of the modelled structure for relationships and data. Based on established research findings and theories, CFA tests existing hypotheses about the factors' structure. The researcher assigns the number of factors, several variables associated with each factor, and the relations between factors. Model fit indices such as Chi-square, RMSEA, TLI, and CFI test whether the data fits or rejects the modeled structure(Hair et al., 2019).

Table 3-3– Exploratory and Confirmatory Factor Analysis

	Exploratory Factor Analysis	Confirmatory Factor Analysis
Reductionist	It is beneficial for condensing extensive datasets with numerous indicators. It also aids in identifying any overlap or ambiguity in indicators, particularly in cases where they may measure multiple constructs simultaneously.	Ensure that each indicator loads exclusively onto one construct, preventing ambiguity and enhancing the clarity and precision of the model.
Matrices	Correlation matrices are commonly utilized, yet they pose challenges when comparing parameters across different samples.	It uses a covariance matrix and is more adept at handling comparisons across samples. Using the covariance matrix, SEM is better equipped to manage comparison across samples, offering greater robustness and accuracy in parameter assessments.
Rotation	Considers data rotation	It does not consider rotation

3.5. System Modelling and Simulation

Systems thinking provides tools for better understanding complex management problems. A key recommendation from system thinkers for problem-solving is to shift the focus from addressing the

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deficiencies of the internal system structure to improving the performance under study. Systems consist of interacting events and their causes within system boundaries (forms, structures, or organisations), forming an interdependent element group that creates a unified pattern to function as a whole (Kirkwood, 1998). The underlying philosophy of system thinking that underpins system dynamic modelling is shown in Figure 3-3, which urges that reactive solutions emerge by making decisions in the system based on the problem's symptoms (events), which are considered to represent short-term solutions that often are end of pipe treatments or firefighting methods. The second layer of solutions to system problems is providing predictive or deductive models by observing and analysing the recurring pattern of the system behaviour. The third layer, which system thinking stresses, is modelling the system structure and the business's internal processes to leverage the root causes of the system problems and assist decision-makers in designing sustainable and adaptable policies that hurdle these issues.

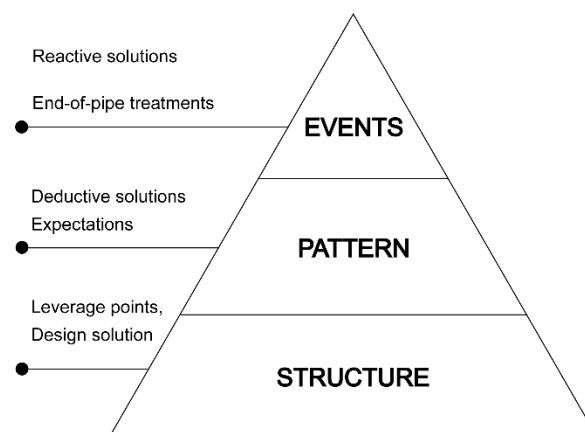


Figure 3-3 – The components of a system.

System modelling involves formulating assumptions and abstractions to depict real-world problems within a system, aiming to resolve them. These problems often present inherent complexities that render direct resolution in the real world challenging, primarily due to associated risks about time, cost, safety, and the system's dynamic nature (Coyle, 1997). System modellers can operationalise theoretical constructs and apply dynamic hypotheses to pose "what-if" inquiries, assess potential benefits and risks, discern patterns, and scrutinise feasibility (Love et al., 1999).

The simulation model is an executable model that runs to build a trajectory of the system's state changes, produced and observed as the dynamic model runs. Figure 3-4 shows three distinct methods of system model simulation; determining the most appropriate method can be done through the following steps: (i) map the real world to models, (ii) identify abstraction level, (iii) determine the model

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language. Various forms rule the simulation methods in Figure 3-4, including differential equations in System Dynamics Modelling (SDM), state charts in Agent-Based-Modelling (ABM), and process flow charts and schedules in Discrete Event Simulation (DES). Along with the advancement of modelling methods, technologies, and the computing powers of Central Processing Units (CPU), simulation modelling applications have expanded to many applications and research arenas (see examples in Figure 3-4).

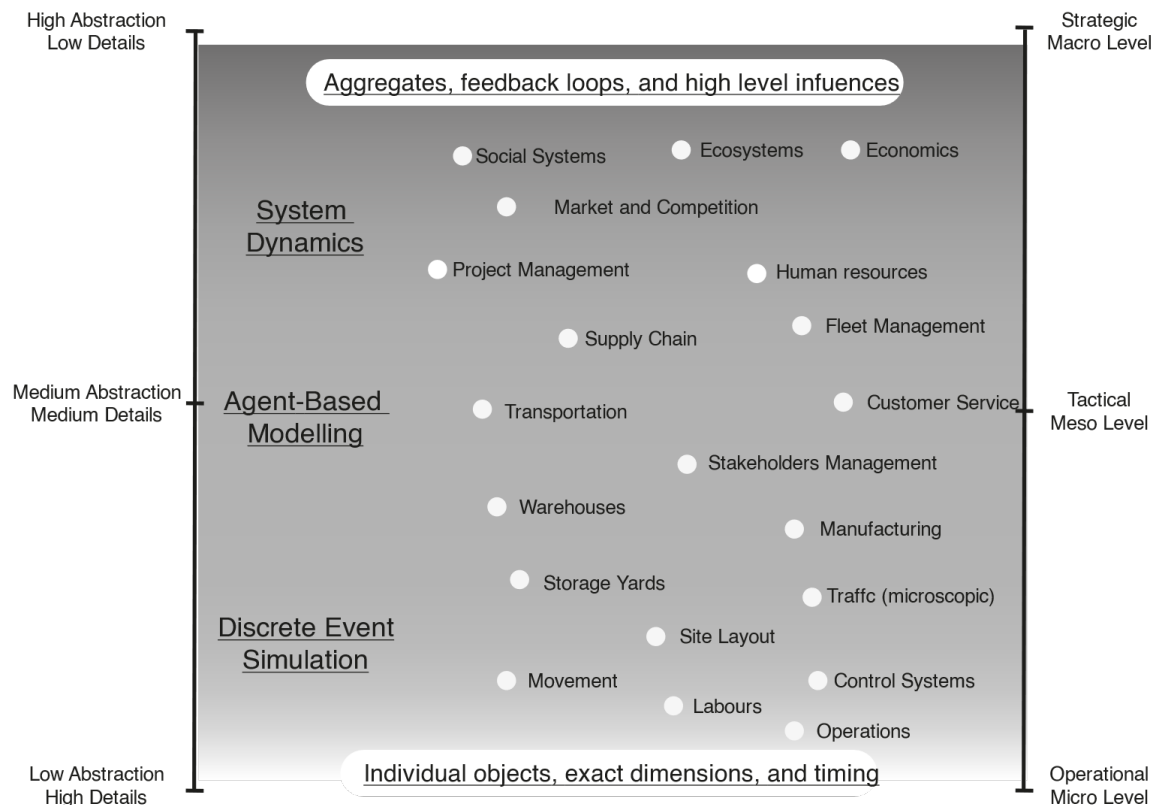


Figure 3-4: A comparative view of three standard simulation methods according to their abstraction, detailing, and analysis levels (Borshchev & Ilya Grigoryev, 2020).

3.5.1. System Dynamics Modelling (SDM)

System Dynamics (SD) was coined in the 1950s by Jay Forrester to depict the change in socio-economic systems' behaviour over time and seek path (history) dependence between variables, thereby providing a way to understand and solve problems (Forrester, 1961). SDM is a feedback-oriented and accumulation perspective that sums the integrals of behaviour for complex systems over time and simulates extractions of a real-world structure by using key variables instead of representing the whole actual system. SDM does not suggest methods to solve the problem but instead increases understanding of the problem. It streamlines a holistic view of a system that micro-level analysis

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methods cannot capture. In the case of micro-level analysis, methods for identifying and quantifying construction waste (e.g., work sampling and resource balance charts) are commonly used, but without explaining the factors that influence waste or their negative impacts on the whole project's elements. (Han et al., 2012) explained that the lack of usage of macro-level analysis methods such as SDM among the construction stakeholders is because they do not provide guidelines on improving project performance.

The process of SDM consists of four phases: conceptualisation, construction, testing, and application, as shown in Figure 3-5 (Zlatanovic, 2012). The first phase is problem formulation and system conceptualisation. This phase's primary outcome is producing a Casual Loop Diagram (CLD). The following phase, "the model construction," uses the CLD produced in the previous phase to specify the stock and flow diagram (SFD); a mathematical model is used in this stage to define the rules that determine changes in SFD. This stage includes visual representations of behaviour changes over time. The third phase consists of three tests to analyse, optimise and compare the model against real-world behaviour. The final stage concerns the application of the SDM, which introduces new policies, strategies, rules, and critical decision points to the real-world system.

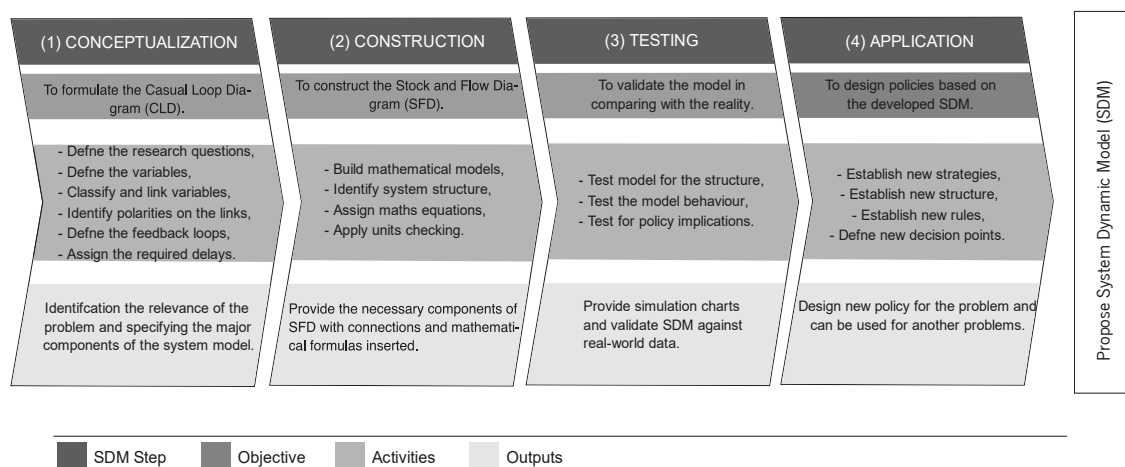


Figure 3-5: The process of System Dynamics Modelling (SDM)

3.5.2. Casual Loop Diagrams (CLD)

A casual Loop Diagram (alternatively called 'influence diagram' or 'system map') is a conceptual and qualitative representation that describes positive and negative feedback (Coyle, 1996). It assumes a holistic view of a problem by focusing on behavioural trends and their relationships with management strategies (Love et al., 1999). CLD forms closed loops and maps the causes and effects among

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individual system variables that can explicitly depict the direction and the type of causality among the significant factors. CLD specifies the system boundary and defines the hypothesis depending on the drawn causal loop. CLDs can vary from project to project, but general themes and structures should be similar (Love et al., 1999).

Causality Type	Representation
• Open Loop • Linear View of Causality	
• Closed Feedback Loop • Dynamic View of Casuality	
• Closed Feedback Loop • Dynamic View of Causality • Information about Internal change	

A typical CLD comprises five components: nodes, links (connections), polarities, feedback loops, and delays (Barbrook-Johnson & Penn, 2022). The nodes can be visualised with boxes or circles representing the system's changing variables. The link is visualised as a connection arrow line from one variable to another; this means the direction of the causal relationship between variables. The polarities are placed at the top or below the arrowheads to determine whether the value increases (plus) or decreases (minus), which determines the magnitude of cause and effect relationship. Determining the feedback loops depends on the number and types of polarities in that loop.

A generic CLD represents the cause-and-effect relationship, indicated by the arrow linking each variable. The plus or minus indicates the direction of causality between variables. Suppose the count of

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negative polarities is odd. In that case, the loop type is a balancing loop represented with a "B" letter, as shown at the centre of the right side of Figure 3-6. while reinforcing loop "R," which is the loop that contains even negative polarity counts or all the polarities that are positive, as shown in Figure 3-6 on the left side. This step is essential in forming the system behaviour, as shown in Figure 3-8. The delays in CLDs are visualised as two parallel vertical lines in the middle of the connection link. In this stage of SDM, the delay is waiting for material and information to be received, processed, requested, or transferred.

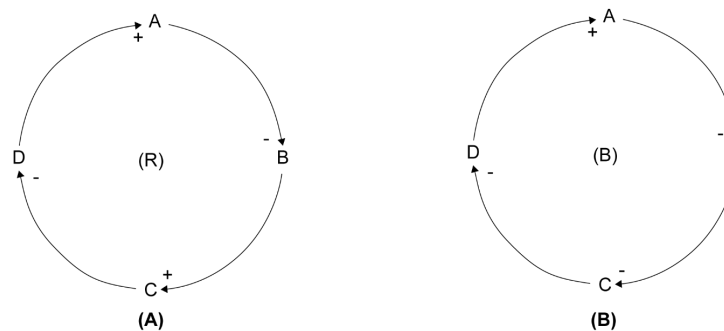


Figure 3-6 - CLDs of positive feedback system (A) and negative feedback system (B)

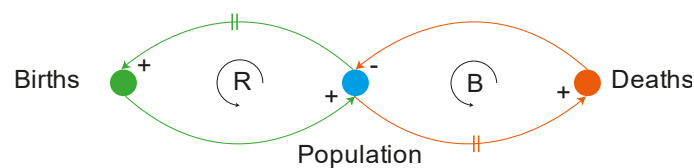


Figure 3-7: An illustrative example of essential elements of Casual Loop Diagrams (CLDs)

Radizicki et al., 1997 described the overall ripple effect in the balancing loops system.

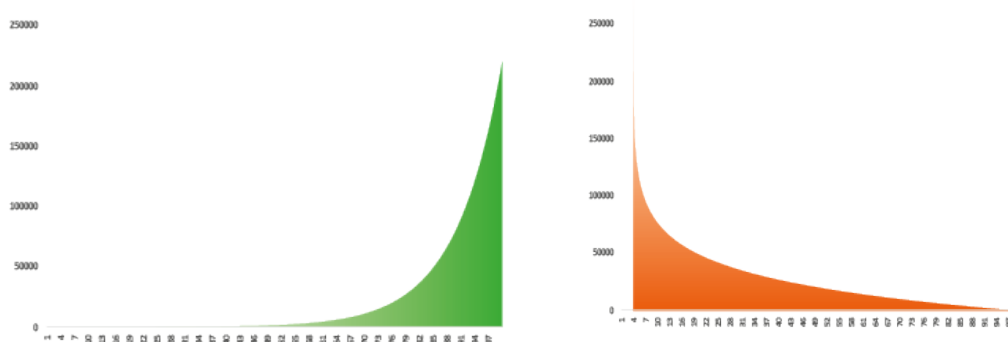


Figure 3-8: (Left) Exponential Growth behaviour when the reinforcement loop is dominant, (Right) exponential decay at the right when the balancing loop is dominant.

3.5.3. Reference modes

As defined by (Saeed, 1998), reference modes represent graphical depictions of key variables' behaviour within a system across time. These visual representations elucidate the system's overall dynamics and are invaluable for referencing system behaviour. Typically, time is represented on the horizontal axis, while the vertical axis denotes units of the variables. The temporal evolution of critical variables provides insights into analysing the model's behaviour pre-, during, and post-its construction.

Reference modes play a crucial role in understanding the underlying structure of the model by visually capturing historical data. They also assess the model's acceptability post-construction, as Sterman (2002) highlighted. During the conceptualization phase, two primary modes are typically developed: historically observed and hypothesized reference modes. Historical reference modes are constructed utilizing historical data, and comparing the model's output to these modes aids in the validation stage of System Dynamics Modeling (SDM) construction. Any discrepancies between the model's behaviour and historical observations necessitate re-evaluation and potential rework (Saeed, 1998).

Moreover, Kirkwood (1998) elucidates four common behaviour patterns that process structures generate. The patterns in Figure 3-9 are frequently observed individually or in combination with business processes. Understanding the types of system structures that typically give rise to each pattern is imperative for practical analysis and management of business processes.

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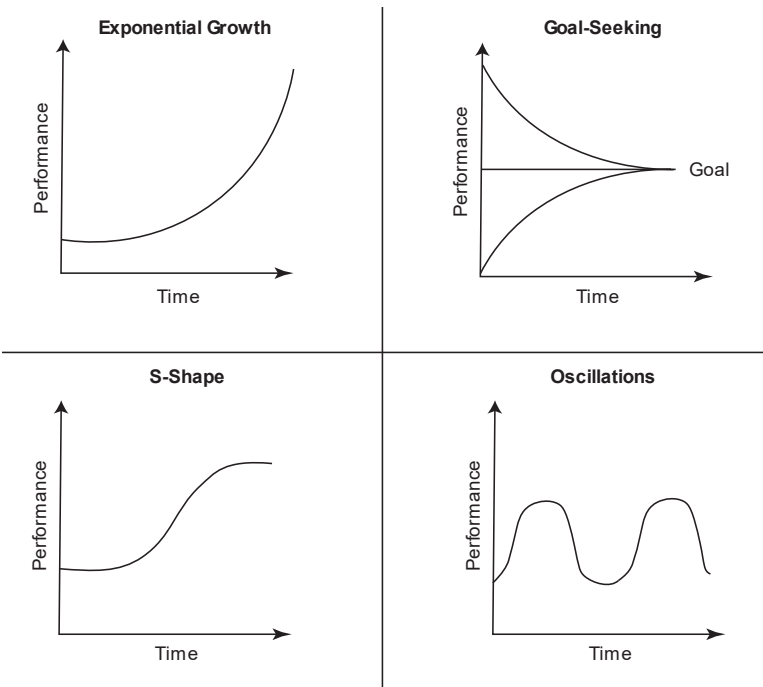


Figure 3-9 - Common reference modes (Kirkwood, 1998)

3.5.4. Stock and Flow Diagram (SFD)

In the model formulation phases of SDM, CLDs are transformed into Stock and Flow diagrams (SFDs). In typical SFD, there are six types of objects, as shown in Table 3-4. The Stock element refers to a real-world process's levels, accumulation, and aggregations over time. Stocks change through Flow elements, therefore defining the dynamicity of the system. The cloud element of SFD refers to irrelevant information to the model or information that leaves the model without affecting the Stock or the flow. Dynamic variables are auxiliary or intermediate functions that dynamically interact with the stocks and flow in the system. Parameters are similar to dynamic variables but are static values that provide the system boundary variations or conditions. Dynamic variables and parameters are connected to SFD using links identical to those used to formulate CLDs. Table functions represent a series of collected data containing functions as arguments and values. Mathematical formulas are necessary to drive changes in the SFD models, as the next section discusses the foundations of stock and flow calculations.

Table 3-4: The components of the Stock and Flow Diagram

SFD components	Definition	Legend
Stock	System levels, states, accumulation, and integrations are only	 Stock

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	controlled by change rates (flow); another stock level cannot directly influence the stock level.	
Flow	Changes (or rate of changes) in each situation	
Cloud	It is a state used when the information is irrelevant to the purpose of analysis.	
Dynamic and static Parameters	Intermediate concepts that consist of functions of stocks and affect flows. Constant values form the boundary conditions for the system.	
Table Functions	A function is defined as a table using an argument and returned value.	
Links	A direct line is a flow other than a flow that connects different SFD components.	

3.5.5. SDM Mathematical Foundations

The Stock and Flow Diagram (SFD) is unchanged without mathematical models working in the simulation software's back ends. From the stock definition as aggregation or accumulation, it is easy to predict the primary mathematical function behind SDM. Figure 3-10 represents the most straightforward Stock and flow diagram that will be used to explain SDM mathematics as expressed in Equation 3-1, which indicates that stock change over time equals the accumulation of difference between inflows and outflows with additions to initial Stock. A numerical approximation is used instead of direct integration, and two standard methods are used for approximation, namely Euler and Runge Kutta methods, which are used for approximation expressed in equations.

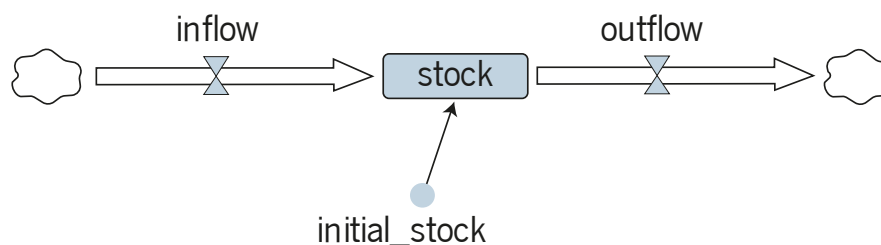


Figure 3-10: Basic Stock and Flow Diagram

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$$stock(t) = initial_stock + \int_{t_0}^t (inflow(t) - outflow(t))dt \dots\dots (Equation 3-1)$$

When t = final time step, t_0 = initial time step, $initial_stock$ = the value that simulation begins with Inflow = the flow that feeds the Stock, outflow = is the stock output.

1. The Euler approximation method, a widely utilized numerical technique, is favoured for its simplicity and efficiency. Unlike more complex procedures, it necessitates only a single equation for calculation. This straightforwardness makes it particularly accessible for various applications. The basic form of the Euler approximation formula is as follows:

$$\frac{d\ stock(t)}{dt} = (inflow(t) - outflow(t))$$
$$stock(0) = s(0)$$

2. The Runge-Kutta approximation formula, often called the RK4 method, is a numerical technique for solving ordinary differential equations. This method is known for its accuracy and reliability but requires a relatively longer computational time compared to more straightforward methods due to the necessity of evaluating four intermediate values, denoted as k 's, to determine the value of the stock. The equations governing the RK4 method are typically represented as follows:

$$k_1 = f(s(t), t) = inflow - outflow$$
$$k_2 = f\left(s(t) + \frac{hk_1}{2}, t + \frac{h}{2}\right)$$
$$k_3 = f\left(s(t) + \frac{hk_2}{2}, t + \frac{h}{2}\right)$$
$$k_4 = f(s(t) + hk_3, t + h)$$
$$stock = \frac{k_1 + 2k_2 + 2k_3 + k_4}{6}$$

3.5.6. Model Validation and Verification Methods

Model validation is critical in comparing the model against reality and similar models performed for the same problem under investigation. Validation should end with accepting or refusing the formulated hypothesis at the first step of SDM. According to Sterman, SDM can be validated through ten methods: 1) dimensional consistency test; 2) boundary adequacy test; 3) extreme condition test; 4) structured assessment test; 5) parameter variation assessment test; 6) integration errors test; 7) behaviour reproduction test; 8) failing member test; 9) surprise behaviour test; 10) structural sensitivity test (Sterman, 2000). The dimensional consistency test verifies whether connected variables have a direct relationship. It is used when developing SFD to expose wrong connections between model elements and highlight irregularities in the model behaviour. The structure test verifies model behaviour compared

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to historical data and produces time-based charts that can be analysed to determine if they are relevant to historical data. Such a test is essential to provide credibility to the formulated SFD. Modellers can compare various custom structures (archetypes) with their model under development.

There are two robustness testing methods: (1) Sensitivity analysis, which is used to verify how the developed SFD is sensitive to small changes, and (2) Parameter variation, the opposite testing method to sensitivity analysis because it tests the model against wider variations.

No model has ever been, nor will ever be, thoroughly validated. Therefore, terms such as "useful," "illustrative," or "reliable" are more apt descriptions for models than "valid" (Forrester, 1961). Attempting to test the validity of a model without a clear distinction of its purpose is meaningless; a system dynamics model addresses specific problems, not general system issues. The confidence we place in a model to help us analyze a given problem should not depend on whether the model can analyze a different problem (Richardson & Pugh, 1981). The basic structure of this research is validated based on project management models, as previously discussed. The Extreme Condition Test determines whether the newly added components can behave realistically under extreme values or policies (Han et al., 2012).

3.5.7. Construction management dynamics

The complexity of construction management is a widely recognized and well-researched area. Overbudget and schedule overhead are common industry problems caused by recurrent changes, workflow interruptions, and information fragmentation. As a result, construction managers tend to use policies to avoid these issues by increasing resources, adding more overtime, push work to execution before refining its constraints, which may have positive outcomes to reduce cost and increase the pace of production, but in the longer run can lower productivity by demotivation, material waste, rework, waiting, quality defects among others.

SDM has been demonstrated as an effective analytical tool in construction project management. To manage such complexity, the SDM must be capable of representing the constituting subsystems with their complex interrelationships and properties.

Interdependencies among project processes

Construction processes exhibit intricate interdependencies, where a change in one process can ripple through others, affecting resource utilisation, spatial allocation, and allocated time. Such changes or interruptions can lead to work blockages, particularly in areas directly impacted by these alterations.

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Construction dynamics

The dynamic nature of construction projects is characterised by various time delays, including schedule execution, error identification, and correction, response to changes in scope or specifications, and waiting for materials or information directives. Additionally, productivity is adversely affected by the diversion of experienced workers' time to train recruits in the short run. To effectively represent, analyse and explain the complexities of socio-technical and managerial systems in construction, Highly developed guidelines that enable the application of system dynamics methodologies

Nonlinear interrelationships

The complex relationship between causes and effects in construction events often defies simple linear modelling. As an analytical tool, system dynamics underscores the nonlinear nature of these relationships in construction (Ford, 2010). For example, overtime may lead to increased fatigue, affecting motivation and ultimately impacting productivity (Lyneis et al., 2001). Such relationships are complex to be represented using linear mathematical functions because they follow nonlinear relationships.

3.5.8. Application of SDM in Construction Management

In the field of construction management research, there is a diverse range of applications, including decision-making and policy analysis, performance assessment, rework and change management, scheduling, risk and contingency planning, resource management, productivity enhancement, cost planning and estimation, project control, bidding and procurement strategies, as well as health and safety considerations (Kedir et al., 2023).

Policy analysis

Decision-making and policy analysis research utilises SDM to analyse various scenarios and support policy development across system-level, high-level, and industry-level perspectives. That includes employing SDM to manage infrastructure projects, such as examining highway maintenance policies and assessing sustainability. Future research should explore incorporating feedback delay into SD models, refining them to analyze policy effects on subsystems and mitigating issues related to policy optimization and scenario analysis. Studying hybrid models can enhance understanding of social impacts in decision-making.

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Performance assessment

Performance assessment in construction management involves evaluating various metrics against predefined standards or benchmarks. SDM has been utilised to enhance performance at the project and organisational levels, addressing areas such as project management quality improvement and overall organisational performance. Future research should focus on expanding SDM models to include more key performance indicators (KPIs) and capturing dynamic relationships between these parameters to determine overall performance. Additionally, understudied factors affecting performance, such as out-of-sequence work, warrant further investigation.

Scope and design changes and rework

Rework and construction project changes significantly impact schedule, cost, and quality performance metrics. SDM research is well-suited for managing these issues because it captures the dynamic relationships between planned activities and causes of rework or changes. Previous studies have focused on understanding these relationships to propose effective mitigation strategies. The research has used SDM to simulate change management strategies and their effects on project planning and performance (Love et al., 1999; D Love et al., 2000; Han et al., 2012). However, there is a stagnation in research on rework causation, possibly due to reliance on traditional methods like questionnaire surveys (Love et al., 2016). Further research is needed to explore qualitative and quantitative aspects of rework causation in different construction contexts and to understand the dynamic impact of changes on the recursive nature of rework during both the design and construction stages.

Planning and scheduling

SDM has been widely employed in project scheduling, particularly in studying the effects of scheduling delays. Early studies focused on mitigating delay and disruption in projects by optimising project duration extensions. Further research explored delays caused by compressing large projects for earlier delivery and investigated dynamic planning and the impact of scheduling in multiple projects. Recent studies have attempted to quantify the effects of various factors on project schedules, highlighting the complexity of achieving planned project milestones solely through schedule-driven management (D. N. Ford, 2002; Lee et al., 2003; Park & Peña-Mora, 2003).

Resource management

SDM can be considered a tool for managing construction resources, encompassing resource allocation, crew management, workforce learning evolution, and crew planning. Additionally, literature has

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employed SDM to assess the influence of resources on various aspects of project performance, including cost, schedule adherence, productivity, and overall project success.

Productivity

SDM offers a comprehensive framework for capturing the dynamics of construction processes and assessing the influence of various factors on productivity. Extensive research has examined numerous factors that affect productivity, including overtime, fatigue, labour motivation, schedule pressure, resource delays, shortages, and workflow interruptions (Lyneis et al., 2001; Porwal & Hewage, 2012). Moreover, recent studies, such as that by Kaya and Dikmen (2024), have specifically focused on evaluating the impact of different working hour arrangements and technologies on labour productivity. This research contributes to understanding workforce management strategies and their implications for overall project performance in construction contexts.

3.5.9. SDM and Lean Construction Research

This section provides a comprehensive overview of studies employing System Dynamics Modelling (SDM) to investigate Lean Construction (LC) methodologies and techniques in the construction industry. Zhan et al. (2022) devised a conceptual SDM for quantity surveying practices, integrating Building Information Modeling (BIM) and Lean principles to delineate intricate relationships among people issues, internal impetus for BIM and Lean adoption, external drivers for LC and BIM implementation and impediments to implementation. Nguyen and Sharmak (2022) employed the Value Stream Mapping (VSM) method to evaluate environmental performance, demonstrating how Lean strategies like the Last Planner System (LPS) and Poka-Yoke reduce processing time and CO₂ emissions. Meshref et al. (2023) proposed a decision-making framework for managing construction material waste throughout the life cycles of industrial projects, integrating BIM and Lean design into the design phase. Omotayo et al. (2020) diagnosed kaizen costing and budgeting practices for construction projects in Nigeria using SDM alongside the Analytical Hierarchy Process (AHP). Studies by Ko and Chung (2014), Ko and Kuo (2019), and Ko (2020) validated Lean Design Processes in formwork workflows, aiming to enhance formwork design efficiency through Lean principles and BIM. Cano and Rubiano (2020) developed a dynamic model to assess improvements in understanding non-value-adding waste within construction processes to enhance economic performance and behavioural aspects. Francis and Thomas (2019) quantified the effects of Lean construction practices on sustainability using causal loop diagramming techniques. Chinda (2009) evaluated effective Lean policies for fostering safety-oriented cultures within construction projects using SDM to explore diverse scenarios manipulating personnel,

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leadership dynamics, partnerships, and resource allocation variables. Collectively, these studies underscore the versatility and efficacy of SDM in investigating and enhancing various facets of Lean construction practices within the construction industry.

3.5.10. Available Software Packages

There are several software tools available for simulation activity as system dynamic modelling, including Experimental Learning Laboratory with Animation (STELLA), Vensim, AnyLogic®, Powersim, iThink®, TRUE, DynaRisk, and Dynamo™ (Kedir et al., 2023). These computer programs are evaluated by comparing the friendly user interface, easy modelling, capabilities of simulation engineering and trying alternative approaches, customizability options, integrability, open source, and programming language, which are displayed in Table 3-5.

The assessment was done by AnyLogic® 8.7.11 professional (concerning other systems considered) conditioned by such parameters as error-checking, compatibility, capability, accessibility, and flexibility. The error checker consists of a Java-based set of rules that accept or reject a particular model structure. The rules are designed to identify inappropriate modelling issues and warn the user about the problem. Furthermore, it enables the smooth import of the models from Vensim, empowering the exchange process and, thus, importing them with other compatible software. The tool also provides a pre-set environment for model testing, enabling the researcher to personalise the test with Java code. Furthermore, the cloud service of AnyLogic® allows model sharing with people who do not have a license or an AnyLogic® account, hence increasing the model's usability among those who lack prior experience in system dynamics.

Numerical solvers for differential, algebraic, and mixed equations are designed as an integration to the AnyLogic simulation engine. Simulation (general simulation, interactive simulation (games and pedestrian simulators)), run comparisons, sensitivity analysis, calibration and optimisation, and Monte Carlo prediction are some of the capacities of the experiment. It has been explained that Any Logic runs on (Meshref et al., 2023).

Furthermore, the ease of using the AnyLogic® software for simulation predictions can be customised using user input to include people having limited experience or no knowledge of system dynamics. It is worth mentioning that AnyLogic may be used to model in discrete event simulation (DES) and agent-based modelling (ABM), hence increasing the analyser's flexibility concerning different levels of depth that can be required.

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Table 3-5 – Comparison between available software packages for System Dynamics Modelling functions

Software Package	STELLA iThink®	Vensim PLE	Anylogic®	Powersim studio	TRUE	DynaRisk	Dynamo™
User-Friendly Interface	x		x	x			
Intuitive Modelling	x						
Advanced Model Building		x			x		
Simulation Capabilities		x	x	x	x		
Analysis Features		x	x				
Multi-Method Simulation			x				
Decision Support			x	x		x	
Customizable Interoperability			x				x
Open Source					x		x
Programming Language		Python	Java	VBScript and C++			Python
License	Commercial	Commercial	Commercial	Commercial	Freeware	Commercial	Commercial

3.6. Conclusions

This chapter serves to delineate the rationale underlying the chosen research methodology. It commences by dissecting established methodologies within construction management, culminating in the discernment of an apt approach harmonising with amassed data and research objectives. The adoption of critical realism and the integration of mixed methods stems from their capacity to transcend singular research paradigms and philosophical orientations. Notably, the strategic inclusion of System Dynamics Modelling (SDM) emerges as a promising avenue for lean construction policy testing, offering a comprehensive framework to address making-do waste and non-value-added inefficiencies. This methodology framework is reinforced by constructing a robust theoretical framework that enhances understanding of the making-do challenge and evolves into a practical research instrument closely intertwined with SDM. Acknowledging limitations, notably the abstract nature of SDM, we envision future possibilities by integrating Agent-Based Modelling (ABM) to enhance realism. In conclusion, this chapter signifies a methodological selection and framework construction, positioning us to methodically unravel the complexities of making-do waste while embracing its boundaries and future potentials.

The next chapter assesses 1) understanding from the literature making-do waste and 2) the expectations of stakeholders on Lean construction planning and control methods and BIM for making-do elimination. Understanding stakeholders' expectations is essential for deploying and accepting the best LC-BIM practices for reducing production waste within the construction industry; the next chapter discusses data collected and analysis processes.

4. Understanding Making-Do

This chapter aims to understand the type of MD waste in construction further. The much-needed synopsis of the literature concerning MD waste emphasises the understanding of the established scientific stream in terms of its definitions, theoretical laws, pathway identification, and methods for detecting and eliminating MD waste. The chapter probes into analysing the existing strategies of MD management, which are classified into five areas: 1) planning and control systems, 2) total quality management, 3) categorisation, quantification, and monitoring, 4) information and communication technologies, and 5) behavioural change management. Then, it provides the causal structure map of the system modelling method that contains the whole relationships between the making-do variables generated in this thesis elaboration. Finally, the chapter outlines a methodological framework that allows the researcher to check the accuracy and authenticity of the logic model.

Except for some changes executed for the formatting and organisation purposes of global information in this document, this chapter integrally presents the work:

Karaz, M. & Teixeira, J. M. C. 2023. A System Dynamic Modelling Approach for Integrated Lean-BIM Planning and Control Methods, Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31), 1220-1231. doi.org/10.24928/2023/0170

4.1. Definition Making Do Waste

Besides the seven production waste classifications of Taiichi Ohno, wastes are also considered by Lauri Koskela; making-do is the eighth type of waste that occurred in construction projects in 2004. MD waste could be defined as initiating tasks without standard resources or proceeding with task execution, although the availability of one of the optimal inputs has ceased (Koskela, 2004; Formoso et al., 2011). MD is considered a widespread waste across the construction supply chain (CSC) chain. However, MD is still a not widely recognised waste in the particular sphere of scientific research (Emmitt et al., 2012). Whereas Fireman et al. (2013) recognised that the inefficiency caused by MD brings about within the construction industry, other sectors undervalue its importance. However, few incentives aim to counteract the prevalent MD culture.

The foundation of the MD concept informed Koskela's (2004) exploration by three pivotal works: 1) The complete kit concept from Ronen (1992), 2) the notion of task soundness (Ballard, 2000), and 3) negative inputs for construction task Koskela (2000). On the other hand, Formoso et al. (2011) maintain that Ronen's principle is insufficient to reflect intricate workflow upstream. Moreover, this limitation arising from an oversimplified decision categorisation is what Koskela (2004) believed to overlook binary choices that are not clearly expressed as dual options. Altogether, the breadth of input reaches beyond the traditional 4M (Management, Material, Method, Manpower) principles and fuses a multitude of factors. However, Emmitt, Pasquire, and Mertia (2012) criticise Koskela's MD definition for being input-cantered, and it does not include output dimensions, thereby not capturing situations where tasks are intentionally left not completed based on preferring an outcome as the best. The production concerns behavioural aspects and is not universally aligned with Koskela's model. Pursuing "Good Enough" standards interfaces with production fluctuations, contributing to process irregularities.

Koskela (2004) referred to the root causes of MD as the underlying theoretical models of the conventional view of construction production, which comprises three models: (1) Managing as Planning and Push Type of Production: this model posits that managing solely through planning tends to generate a push behaviour, wherein tasks are pushed forward regardless of readiness or the availability of requisite resources. (2) Thermostat Model: According to this model, Making Do is employed as a strategy to prevent performance slippage, where the gap between standard performance and actual performance is minimised. It serves as an adjustment mechanism to maintain alignment. (3) Classical Communication: This model involves one-way communication during execution, where notifications to initiate a task occur without consideration for the resources at hand and without involvement in the knowledge of downstream players in the decision-making. The act of commencing activities is prioritised

4. Understanding Making-Do

over the available resources or conditions.

It is essential to recognise that no project operates within an ideal environment. Even lean projects encounter unmet prerequisites (Pikas et al., 2012). For example, crew leaders, also known as Last Planners, often make MD decisions even after the crew has committed to the weekly work plan, asking themselves if they must "wait" for input or "go" without input. MD is dispersed across the supply chain among clients, procurement, designers, prefabrication, and site (Koskela, 2004). MD depends on its specific occurrence within a localised context (Dos Santos et al., 2020) and constitutes a prominent form of waste that can and should be eradicated from cultural norms, operational processes, and habitual practices (Alhava et al., 2019).

While progress in the chain of waste studies was gaining momentum, most of the research remained entirely theoretical (Fireman & Saurin, 2020). At the time of writing, no study had given a model of the actual chain of wastes. This gap impeded the study's operational significance of practical applications. There are yet no direct assessments of the whole MD, and their importance is underestimated in different modelling methods, as these methods cannot reasonably capture all the key constituents and features of the MD's complexity (Koskela, 2004). Nevertheless, the indirect evidence reveals its existence with a possible assumption that the source of the problem will often be held responsible differently as the upstream process management activities are neglected (Formoso et al., 2011).

4.1.1. Root Causes of MD

Figure 4-1 shows that the occurrence of making do unfolds in distinct phases. Initially, it emerges when an optimal input is absent, attributed to social, economic, technical, or managerial factors. Decision-makers then face a choice: either proceed with the task without the necessary input or engage with relevant stakeholders to address the deficiency. If external pressures persist, be they economic, technical, social, or managerial, and the workflow continues without resolution, making do leads to either innovative solutions or waste generation. Swift resolution is essential to prevent production bottlenecks. Notably, if the waste resulting from making do remains unnoticed until the quality inspection stage, subsequent reworks might become imperative. This process underlines the necessity of fast response to short-term problems and informed decisions in the face of production interruptions.

4. Understanding Making-Do

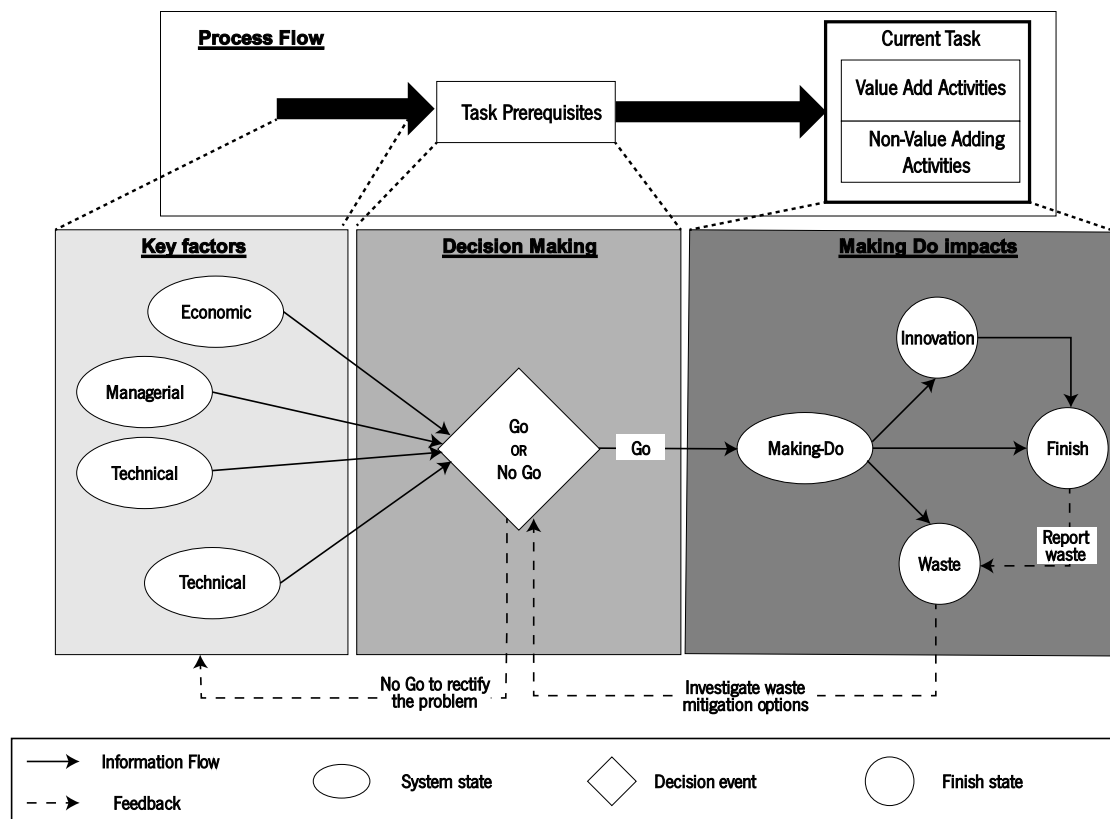


Figure 4-1- A conceptual diagram of making-do phenomena.

In the pursuit of understanding the underlying factors contributing to the phenomenon of MD, several studies have illuminated its origins (Alhava et al., 2019; Fireman et al., 2013; Formoso et al., 2011; Hamzeh et al., 2012; Koskela, 2004; Leão et al., 2014; Pikas et al., 2012). This section systematically categorises the primary drivers of making do into four classifications: economic, technical, managerial, and social. These causal factors have been identified through an extensive literature analysis and are presented in Table 4-1.

The economic category broadly includes budget constraints, time limits, and contractual obligations that force workers to follow rules and complete tasks despite insufficient resources. Therefore, workers often improvise ways to finish tasks within the time frame by using readily available materials. Technical challenges arise from the perception among tradespeople that functions should be initiated to secure work rather than engaging in discussions with higher-ranking personnel. Additionally, inadequate analysis of task prerequisites before moving them from backlog to the active work roster and the failure to address task constraints contribute to technical issues. Congested or unmanaged work areas, leaving tasks unfinished and informal completion of packages, lead to complications such as "re-entrant flow."

4. Understanding Making-Do

The managerial aspect involves inefficient resource management and allocation. Insufficient incentives to discourage making do foster a culture where makeshift solutions prevail. Furthermore, a lack of documented learning opportunities from past making-do incidents, breakdowns in communication, and fragmented functions between quality management, planning, and control contribute to the problem.

Lastly, the social dimension pertains to soft factors, including common understanding, trust, traditional push production mindsets, and the tendency to handle one task with multiple individuals at different times, hindering the learning curve for specific operations. Additionally, there is an attribution error concerning task requirements, which further compounds the challenges of making do. This detailed analysis in Table 4-1 provides insights into the multifaceted nature of making do, shedding light on its complex interplay of economic, technical, managerial, and social factors.

Table 4-1 - Summary of Causal Factors Contributing to Making Do in Construction Projects

CAT	MD causes	Reference
Economic	Initiating work due to budget and time pressures.	(Fireman et al., 2013a; Formoso et al., 2011; Hamzeh et al., 2012; Koskela, 2004)
	Force starts to avoid contractual penalties.	(Emmitt et al., 2012; Pikas et al., 2012)
	Shortage of skilled workers, equipment, tools and materials	(Emmitt et al., 2012)
	Lack of monetary finance, incentives, and rewards.	(Koskela, 2004)
	Initiating the job to secure the work.	(Koskela, 2004)
Technical	Improper constraints analysis during LAP and Make-ready phases	(Emmitt et al., 2012; Fireman et al., 2013a; Fireman & Saurin, 2020; Pikas et al., 2012)
	Conflicts in space utilisation, crowded or empty locations	(Emmitt et al., 2012)
	Uncertainty in means and end, variability in product and process	(Leão et al., 2014; Pikas et al., 2012)
	Leaving small works behind to form unfinished works	(Leão et al., 2014; Emmitt et al., 2012; Fireman et al., 2013)
	Delay in resources supply	(Emmitt et al., 2012; Fireman et al., 2013a; Hamzeh et al., 2012)
Management	Lack of MD management incentives	(Emmitt et al., 2012)
	Excluding downstream from upstream decisions	(Hamzeh et al., 2012)

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Social	Undocumented learning opportunities	(Emmitt et al., 2012)
	Breakdowns in communication	(Amaral et al., 2022; Koskela, 2004)
	Lack of integrated control between quality and plan management	(Fireman et al., 2013a; Formoso et al., 2011; Leão et al., 2014)
	Absence of common understanding	(Emmitt et al., 2012; Fireman & Saurin, 2020)
	Various individuals handle the same task.	(Emmitt et al., 2012; Fireman et al., 2013a)
	Attribution error in task requirements.	(Emmitt et al., 2012)
	Push production mentality.	(Alhava et al., 2019; Koskela, 2004)
	Lack of trust in supplier input.	(Koskela, 2004)

4.1.2. Characteristics of MD

Moving from the root causes of MD, it is essential to identify the main attributes of MD after emergence. Bølviken & Koskela (2016) characterised MD as a complex and interrelated phenomenon, posing considerable challenges in avoidance, owing to its simultaneous occurrence due to rational and irrational decisions. MD is a moderating factor and leads to waste within construction waste chains (Fireman & Saurin, 2020). The existing mental models to understand MD phenomena lack a functional orientation, making it challenging to trace back to their root causes (Fireman & Saurin, 2020).

Even minor MD incidents can have disproportionate consequences. While they might only cause a localised impact, they can exert a substantial global influence on the entire production system (Fireman & Saurin, 2020). Although additional resource allocation might address MD originating at the initial stages of a waste chain (thus preventing contractual penalties due to scheduling delays), they can still engender new forms of waste downstream (Fireman & Saurin, 2020).

The association between MD and other types of waste is not unidirectional; instead, it can occasionally be cyclical (Perez et al., 2015). This cyclic nature poses challenges in discerning the initial point of occurrence, as indicated by Bølviken & Koskela (2016), who have pointed out that waste chains do not adhere to a linear progression.

Fireman and Saurin (2020) and Saurin and Sanches (2014) have undertaken endeavours to comprehend the attributes of MD through the lens of the Resilience Engineering (RE) approach, employing the four principles of the Functional Resonance Analysis Method (FRAM). In resource scarcity, "Approximate Adjustment" in MD involves adapting improvisation to overcome limitations.

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"Emergent Behaviour," MD emerges from intricate variable interactions, yielding unexpected production outcomes due to uncertainty and variability. The "Equivalence of Success and Failures" principle highlights the value of learning from positive and negative MD incidents. In "Functional Resonance," MD manifests across levels—individual, team, and organisational—stemming from diverse contextual functions. Again, this non-linear behaviour of MD often traces back to a singular root cause, illuminating complex production system interconnections, which is delineated as interaction within a complex social system (CSS).

4.1.3. The relationship between MD and other construction issues

This section interprets the relationship between MD and pivotal construction management phenomena, including buffering, variability, uncertainty, improvisation, and unfinished work. Comprehending these associations makes it feasible to augment comprehension of these phenomena. While exploring MD waste, Koskela (2004) discusses the concept of buffering and its stark contrast with MD. Buffering entails the temporary halt of materials awaiting processing, introducing a pause in the workflow. In contrast, MD involves negative waiting time, depicting scenarios where tasks progress without the complete standard inputs or even commence without at least one essential input.

Fireman and Saurin (2020) emphasised that variability in both product and process has a substantial connection to the occurrence of MD. Particularly in complex systems such as construction, unforeseen variability is prevalent. Consequently, implementing a margin becomes imperative, serving as a proactive measure to prevent the immediate conversion of "making-ready" failures into instances of MD waste. In this context, slack is pivotal as an early indicator that operational performance diverges from the parameters defined by standardised operating procedures. Recognising the inevitability of a considerable degree of variability, prudent preparation for such circumstances becomes essential (Bertelsen and Koskela, 2005). Furthermore, the research accentuates that forestalling and mitigating the repercussions of MD can reap benefits from proactively identifying sources of variability and formulating corresponding slack resources.

Pikas et al. (2012) establish a correlation between uncertainty and the phenomenon of MD. Pikas cited Winch's (2010) definition of uncertainty, which is characterised as the absence of essential information required by the project team for task execution, which remains unattainable. Notably, 90% of 345 recorded MD cases were attributed to uncertainty (Formoso, 2011). Uncertainty can engender defensive lose-lose behavioural patterns when planning is obscured by uncertainty. Within this context, MD decisions become primarily steered by risk aversion rather than the pursuit of optimal benefits for all parties involved.

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The phenomenon of MD is closely intertwined with improvisation. Improvisation, a prevalent people practice, finds its presence even within well-structured business organisations (Formoso, 2011). Its significance becomes particularly pronounced when established rules and methods fall short (Formoso, 2011). The frequency of improvisation tends to escalate in the face of unpredictable events or pressing urgencies that necessitate immediate responses (Cunha, 2004; Hamzeh et al., 2012). Hamzeh et al. (2012) establish a connection between people's attitudes towards improvisation and the characteristics of a project, encompassing factors such as complexity, delivery method, time constraints, company rigidity, design challenges, and project type. It is within this interplay that the concepts of MD and improvisation are entwined. It is worth noting that improvisation often intertwines with the notion of MD. While these terms overlap in specific contexts, their distinct differences lack precise delineation within the literature.

Fireman (2013) illuminated a strong correlation between MD and the emergence of Unfinished Works waste. The phenomenon of Unfinished Works, as observed by Sukster (2005), can often be attributed to a lack of harmonisation between Production Planning and Control (PPC) and Quality Management (QM) processes. This misalignment can result in tasks within short-term planning packages being prematurely deemed completed, leaving many small tasks unattended for the following week (Fireman, 2013). These instances of unfinished work are frequently associated with rework or incomplete tasks, potentially contributing to an upsurge in Work-in-Progress (WIP). Such scenarios can distort the accuracy of PPC by erroneously marking work packages as finalised when additional work is still required in subsequent weeks. The nature of these unfinished works predominantly involves new work packages and rework, which are often excluded from short-term planning. These situations frequently encompass Non-Value-Added (NVA) activities, such as setup, movement, and residue removal.

Similarly, Emmit et al. (2012) noted that MD frequently results in left unfinished tasks, leading to "unfinished works." This circumstance necessitates subsequent rectification of functions. Such an occurrence is often linked to evaluating prior work as acceptable, allowing the following trade to proceed. As introduced by Brodeskaia (2010), the concept of Re-entrant Flow underscores the consequences of planning based on individual tasks rather than adopting a location-based and standardised batch approach. Organising work around specific locations and standardised batch sizes, facilitated by a Location-based Management system (LBMS), minimises unnecessary movement. This strategic organisation empowers trades to complete tasks within a designated unit before transitioning to the subsequent batch, thereby fostering operational efficiency.

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4.1.4. People's behaviour Towards MD

As discussed in the first section of this chapter, the decisions in construction projects can lead people to make the following decisions: (1) Abandonment of the planned work, (2) Improvisation or MD (Pikas et al., 2012). These decisions are influenced by behaviours toward production, which vary among people in the construction industry regarding attitude, modes of thinking, and freedom to engage as necessary proactively (Hamzeh et al., 2012). According to the case study by Hamzeh et al. (2012), construction practitioners differentiated between white-collar and blue-collar people. Blue collars were found to be more pragmatic and innovative but localised to their execution stage. On the other hand, top management's decisions were found to be more sensitive to time and cost restrictions than blue-collar people, as well as there is little innovation in their decisions, where their efforts often focus on strategic planning, establishing timelines, and scheduling tasks.

According to Javanmardi et al. (2019), a comparison was made between the behaviour of construction practitioners in China and the USA concerning MD. They found that construction managers in China may not encounter variation in project duration due to their preference for MD, while in the USA, MD may exhibit a significant influence on project duration. Javanmardi et al. (2019) show that construction practitioners in China tend to rely on making-do practices without significantly affecting project durations, whereas, in the USA, making-do behaviours substantially impact project timelines. This result suggests that the approach towards making do among construction managers differs between the two countries, potentially influencing project outcomes and durations accordingly.

Javanmardi et al. (2019) study has rejected if there is any variation of MD impact when different management levels are responsible for MD decisions. However, Hamzeh sees that the perception of MD decisions can differ between management levels, where the attitude towards MD differs. Thus, there is a difference in the perception of MD decisions among management levels, suggesting potential disparities in attitudes and approaches towards MD within construction management hierarchies. Therefore, these findings underline the complexity of MD and highlight the need for nuanced analysis when considering its impact on construction projects.

4.1.5. Essential Prerequisites for Construction Process Execution

Figure 4-2 depicts a protocol for managing Making-Do practices and corresponding reporting mechanisms. This protocol establishes the relationship between the categories of emerging Making-Do practices and their impacts, highlighting the essential inputs required to execute work packages based

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on the works of (Dos Santos et al. 2020) and (Sommer 2010).

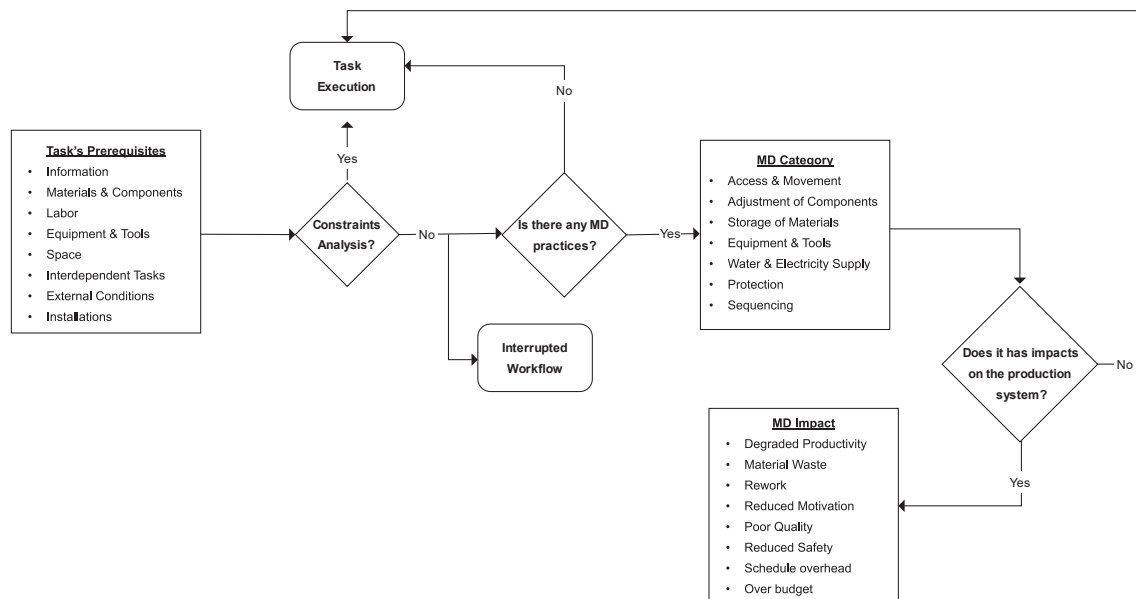


Figure 4-2- A diagram illustrating the relationships among prerequisites, MD categories, and impacts based on the protocols developed by Dos Santos et al. (2020) and Sommer (2010)

Table 4-2 summarises the essential prerequisites for executing construction processes, sourced from Koskela's (2000) and Sommer's (2010) works. Table 4-2 detailed insights into each requirement per these exploratory studies, defining seven fundamental construction flows comprising information, materials and components, labour, equipment and tools, physical space, interdependent tasks, and external conditions. From the necessity of comprehensive work plans ensuring detailed project information to the availability of skilled labour and functional tools and equipment, each prerequisite holds significant importance. Furthermore, this table details the importance of understanding interdependencies between tasks, accounting for external factors like weather conditions, and providing temporary facilities. Grasping these prerequisites is paramount for project managers, as they ensure a well-prepared and efficiently functioning construction environment, thereby enhancing project outcomes and minimising disruptions.

Table 4-2 - Prerequisites for Construction Project Execution and Their Explanations, Sourced from Koskela (2000) and Sommer (2010)

Prerequisite	Explanation
Information	The presence of comprehensive work plans with adequate information
Materials and Components	The availability of materials and components ensures adherence to project specifications and standards regarding quality and quantity.

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Labour	Availability of the necessary human resources in terms of both quantity and qualifications.
Equipment and Tools	The availability and proper functioning of the required tools and equipment are essential for successfully executing tasks.
Space	Ensuring adequate workspace availability, well-defined circulation routes, and sufficient storage areas for materials is essential for uninterrupted project operations.
Interdependent Tasks	Activities with strong interdependencies can impact the execution of subsequent tasks.
External Conditions	External factors, such as weather conditions, including wind and extreme temperatures, play a significant role in project planning and execution.
Installations	Availability of provisional electrical and hydraulic installations, site security facilities, scaffolding, area closures, and storage zones

4.1.6. Making Do Categories

Table 4-3 categorises various aspects of Making-Do (MD) practices in construction projects, shedding light on the complexities involved. The first set of categories delves refers to the physical elements essential for task execution. 'Access/Movement' delineates spatial considerations, emphasising the need for unobstructed access and clear pathways for labourers. 'Component Adjustment' highlights the adjustments made to construction elements, often unplanned, to ease installation. 'Working Area' assesses the appropriateness of the work zone, ensuring conducive surroundings for task execution. 'Storage' underscores the significance of preparedness, providing adequate storage of tools, materials, and components. 'Equipment/Tools' reflects the adaptation or development of tools for efficient usage during tasks, while 'Water and Electricity Supply' focuses on establishing the necessary infrastructure for a seamless energy supply. 'Protection' evaluates the availability of suitable conditions for implementing protective measures. The final category, 'Sequence,' delves into the deviation from the intended construction process, pinpointing instances where tasks stray from the planned sequence. The sources, primarily Formoso et al. (2011), Sommer (2010), Fireman et al. (2013), and Leão et al. (2014), provide a comprehensive foundation for understanding these categories. This detailed categorisation offers invaluable insights into the multifaceted nature of MD practices, providing a basis for construction professionals to address and mitigate these challenges effectively.

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Table 4-3– Making-Do Categories and Descriptions in Construction Projects

MD Category	Explanation	Source
Access/Movement	Relating to the spatial considerations required to execute tasks regarding sufficient access and clear labour pathways	
Component Adjustment	Unnecessary or unplanned adjustments of construction components or elements to facilitate task completion during installation	
Working Area	Lack of consideration given to the appropriateness of work areas or supporting zones during activity execution.	(Formoso et al., 2011; Sommer, 2010)
Storage	Inadequate preparation was given to sort and store tools, materials, and components.	
Equipment/Tools	Inappropriate development or adaptation is improvised for equipment and tools during usage for task execution.	
Water and Electricity Supply	The inappropriate adaptation or establishment of infrastructure for supplying water and energy.	
Protection	Availability of conditions for protection measures	(Sommer, 2010)
Sequence	Deviation from the intended construction process	(Fireman et al., 2013a; Leão et al., 2014)

4.1.6. Impact of Making-Do Practices in Construction Projects

Table 4-4 provides an in-depth analysis of the diverse impacts of MD practices within construction projects. The social consequences encompass demotivation among workers, particularly when forced into tasks likely to remain incomplete, leading to frustration and extensive communication efforts. This demotivation is exacerbated by the need for return visits to rectify errors, impacting overall productivity. From a technical perspective, MD contributes to delays, extending project durations and processing times. These delays often require additional inspections and corrections, leading to overbudget scenarios due to penalties, rework, and waste. Material wastage occurs when inappropriate materials are employed to compensate for MD-induced delays, sometimes leading to demolitions and corrections

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upon error discovery. Out-of-sequence activities further disrupt project flow, creating illogical task sequences. Rework becomes a common consequence of MD, requiring additional resources and inspections for rectification. Unfinished works initiated informally through MD are often abandoned due to their inability to meet quality standards. Quality deviation is another notable issue, manifesting in defective products and necessitating rework.

Additionally, MD adversely affects productivity, undermining the performance of materials, equipment, and personnel, compromising overall project success. Furthermore, inadequately managed spaces contribute to increased equipment/tool transportation waste and personnel movement across various project locations. This comprehensive analysis underscores the multifaceted negative impact of MD practices, emphasising the urgent need for effective mitigation strategies within construction management practices.

Table 4-4 – Impact of Making-Do Practices on Construction Projects:

MD Impact		Explanation	Source
Social	Demotivation	MD can diminish the motivation of workers who are cognizant of engaging in forced tasks that are unlikely to be completed.	(Ronen, 1992; Koskela, 2004; Formoso, et al. 2011; Amaral et al.2020)
	Frustrations	Workers dealing with challenging tasks may become frustrated, often engaging in extensive communication, especially when missing essential inputs. This frustration can be exacerbated when they must return to rectify errors without witnessing any significant increase in productivity.	(Alhava et al., 2019; Neve & Wandahl, 2018)
	Reduced effort exerted	In the early stages of MD-affected activities, efforts rise temporarily but often shift elsewhere in the long run when issues arise.	(Koskela, 2004)
	Violations of Health, Safety and Environment (HSE) regulations.	Without Health, Safety, and Environment (HSE) instructions, tools, a clean environment, and adequate training can lead to hazardous activities.	(Neve & Wandahl, 2018)

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Technical	Delay (Extended project duration) and extended processing time	MD causes a certain amount of delay, resulting in longer lead times, and is often required for error correction and additional inspections, especially when there are stoppages in subsequent tasks.	(Ronen, 1992; Koskela, 2004; Formoso et al. 2011; Hamzeh et al. 2012; Alhava et al. 2019; Amaral et al.2020)
	Material Waste	MD can contribute to material waste by necessitating inappropriate materials to compensate for delays or inadequacies in material delivery. MD may also lead to demolishing or correcting mistakes once the problem is discovered.	(Koskela, 2004; Formoso, et al. 2011; Amaral et al.2020)
	Sequence activities	Tasks that commence with inadequate preparation, whether due to improper prerequisites or their absence, tend to set off a chain reaction of events that follow an illogical sequence.	(Neve and Wnadahl, 2018)
	Overbudget	Delays, material wastage, penalties for delays, rework, energy inefficiencies, accidents, and injuries collectively contribute to exceeding the allocated budget for each task affected by MD.	(Amaral et al.2020, 2022)
	Overload or vacant work locations	Workers dealing with MD-infected tasks, often caused by inadequate space management, may face disruptions of empty locations or congestion in tightly packed work areas.	(Neve & Wandahl, 2018)
	Rework	Initiating activities without adequate inputs can result in production mistakes and errors, necessitating inspections and allocating additional resources for rectification.	(Ronen, 1992; Koskela, 2004; Formoso et al. 2011; Hamzeh et al. 2012; Fireman et al. 2013; Alhava et al. 2019; Amaral et al.2020)

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Unfinished works	Small, informally carried tasks may be abandoned when it becomes apparent that they cannot be executed correctly through the MD approach.	(É. M. Dos Santos et al., 2020a; Emmitt et al., 2012; Fireman et al., 2013a)
Quality Deviation	MD often results in non-conformance with process and product standards, leading to deviations in the required quality. These deviations are typically manifested as defective products that may necessitate rework.	(É. M. Dos Santos et al., 2020a; Formoso et al., 2011; Koskela, 2004; Sommer, 2010)
Reduced Productivity	The negative impacts of MD are closely linked to the poor production performance of materials, equipment, and personnel, ultimately affecting the overall project's success.	(É. M. Dos Santos et al., 2020a; Formoso et al., 2011; Koskela, 2004)
Moving and Transportation waste	Tasks with inadequately managed spaces are closely associated with increased waste in equipment/tool transportation and the movement of personnel across various locations within the construction project.	(Perez et al., 2015)

4.2. MD Mitigation Strategies

The increased attention that Making Do (MD) waste has received from both the construction industry and academic circles, coupled with recent advancements in Planning and Control (P&PC) methods and Information and Communication Technology (ICT) technologies, has paved the way for the development of several methodologies aimed at aiding professionals in conducting thorough prerequisite analyses for tasks during the planning and control phases to diminish the negative impacts of MD practices. Indeed, the role of computer assistance is vital in construction-related tasks to attain flexibility, reliability, and efficiency (Sacks et al., 2018). Based on these considerations, this section delves into a comprehensive review of existing MD research to evaluate the efficacy and limitations of recommended strategies.

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This section identifies the best practices from the gathered papers. Subsequently, these identified papers were thoroughly examined by manually scrutinising the references cited and placing an additional 25 best practices. Through a thorough assessment of the primary objectives of these strategies extracted from the literature, four broad classifications of practices emerged, which can be summarised as follows:

- i) Making Do identification, categorisation, and quantification.
- ii) Production Planning and Control
- iii) Quality Management and Control
- iv) Information Communication Technologies
- v) Social Empowerment Perspectives

Koskela's discourse posited the imperative for a paradigmatic realignment within the domain of production theories to respond to Making Do practices. Within this context, his recommendations adopt a comprehensive approach to reconfiguring the organisational landscape. The discourse expounds upon Koskela's propositions, which ardently advocate for the managing-as-organisation principles, linguistic-action theory, and scientific experimentation as transformative frameworks. Furthermore, his conceptual purview extends to the nuanced conceptualisation of construction as an adaptive complex system, drawing profound resonance from the insights espoused by Bertelsen (2004).

4.2.1. Production Planning and Control Systems

Pragmatic recommendations also succeed in the above-mentioned theoretical paradigms advanced by Koskela. Among them, he advocates for implementing the Last Planner System (LPS) as an operational methodology while simultaneously emphasising the pivotal objectives of reduction for lead time and inventory as pivotal catalysts for improvement. LPS, as a technical planning system, fosters the formation of a social system among crews. Within LPS, two primary control types can be identified.

Within LPS, two primary control types can be identified.

- 1- **Production unit control:** this form of control enables improved worker assessment through continuous learning and corrective actions.
- 2- **Workflow control:** This form of control focuses on optimising the sequence and rate at which workflows are done across production units.

(Alhava et al., 2019; Amaral et al., 2022; Dos Santos et al., 2020; Emmitt et al., 2012; Fireman et al., 2013; Formoso et al., 2020; Pikas et al., 2012; Sukster, 2005) Advised to focus on planning and control necessitates rigorous control over construction processes, which identifies the minimum or

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essential conditions for initiation, elaborating, and concluding tasks to be accomplished. A particular focus was dedicated to lookahead planning (LAP); its importance comes from constraints analysis, considered an imperative function of LPS. The Make-ready process also plays a pivotal role because it provides crucial operational-level decisions made by the last planners and can involve persistence with ongoing work in progress or resorting to making do. It should also be an action plan to enhance "common understanding" through informal dialogues and visual management (Alhava et al., 2019; Amaral et al., 2022; É. M. Dos Santos et al., 2020a; Emmitt et al., 2012; Fireman et al., 2013a; Formoso et al., 2020; Pikas et al., 2012; Sukster, 2005).

The proposed strategies involve structuring work based on specific locations and standardised batch sizes. The LBMS approach minimises extraneous movement and empowers trades to finalise work within a unit before transitioning to the subsequent batch (Emmitt et al., 2012). Achieving substantive progress necessitates an overhaul of the Takt-Planning Task Control (TPTC) implementation, requiring identifying, isolating, and eradicating the root causes underpinning the waste cycle. These strategies include eradicating cultural norms, habitual behaviours, and operational processes (Alhava et al., 2019).

In summary, combating MD practices requires a comprehensive approach that combines theoretical insights with practical methodologies. Implementing these strategies involves technical planning and control and necessitates cultural and behavioural changes within the construction industry. By addressing root causes, fostering communication, and embracing structured planning, construction projects can mitigate the challenges posed by MD practices and achieve more efficient and productive outcomes.

4.2.2. Quality Management and Quality Control

The foundational principles of Total Quality Management (TQM) emerged as a pivotal transformation in organisational paradigms pioneered by four renowned quality management gurus (Crosby, 1984; Ishikawa, 1987; Juran, 1988; Shewhart & Deming, 1986). TQM has evolved into a significant global competition driver, striving to enhance productivity and internal and external satisfaction. One of the primary objectives of TQM is to elevate both process and product quality by minimising variability in processes and identifying the root causes of product defects.

Quality Management and Quality Control (QM/QC) play instrumental roles in curbing informal practices and makeshift solutions. Ensuring the effectiveness of control implementation involves assigning data processing responsibilities to a single individual, facilitating the harmonisation of control

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measures. This approach resonates with the principle of integrating in-process quality control, a cornerstone of quality management exemplified by the Toyota Production System.

Furthermore, using Statistical Control Charts proves invaluable in assessing the likelihood of errors and evaluating the associated risks of makeshift solutions. By employing these tools, organisations can systematically analyse errors' probability, enabling proactive risk management and reinforcing the commitment to quality standards. TQM, in essence, represents a comprehensive strategy that not only rectifies defects but also fosters a culture of continuous improvement, thereby fortifying organisations against the challenges of a competitive global landscape.

In summary, implementing TQM and QM/QC practices instigates a shift towards a proactive, standardised, and quality-oriented approach within construction projects. This shift inherently reduces the occurrence of MD situations by addressing their underlying causes and promoting a culture of adherence to planned processes.

4.2.3. Information Communication Technologies

Adopting information technology tools and processes for data processing and synchronising control measures to pre-empt make-do incidents is recommended. This integration encompasses operational design utilising 4D BIM, prototyping techniques, and traditional first-run studies (Etges et al., 2020; Formoso et al., 2011; Leão et al., 2014). Alhava (2019) envisions that the digital footprint can mitigate make-do occurrences and optimise task efficiencies (Alhava et al., 2019). Integrating the Internet of Things (IoT) and mobile applications for task transactions, changes, task assignments, and inspections can bring MD incidents to the fore, aiding predictive analysis and decision-making to mitigate the adverse impact of such occurrences.

Research emphasises the importance of shared understanding and effective crew planning (Emmitt et al., 2012; Pikas et al., 2012). Planning systems like the LPS reduce MD (Formoso et al., 2011; Fireman et al., 2013). Hamzeh et al. (2012) discuss the complex relationship between improvisation and planning, while Emmitt et al. (2012) recommend planning tasks around locations to reduce unnecessary movement by using a location-based management system (LBMS). The combination of Building Information Modelling (BIM) with LPS has also been highlighted as an effective strategy to enhance planning and reduce MD waste (Saurin & Sanches, 2014; Leão et al., 2014; Dos Santos et al., 2020; Amaral et al., 2022; Etges et al., 2020; Igwe et al., 2022).

Managing MD requires enhanced planning, proactive approaches, technology integration, and transparent tools that reflect reality and are simple to understand (Tezel et al., 2016). Addressing MD improves project performance and efficiency. That involves viewing MD through the lens of Resilience

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Engineering for a nuanced understanding, integrating production and quality control using IT and dynamic spreadsheets and risk analysis for improved planning.

4.2.4. Social Empowerment Perspectives

Enhancing the attitudes of tradespeople, supervisors, and site managers to deter Making-Do (MD) practices is paramount for increasing productivity and reducing defective products (Emmitt et al., 2012). This knowledge necessitates a cultural shift achieved through training programmes to enhance communication, collaboration, and skills, enabling individuals to handle uncertain situations that often lead to MD practices. Training and learning initiatives should cover fundamental concepts such as MD, variability, unfinished works, and other aspects of production waste derived from lean construction theory. Additionally, these programs should educate individuals on best practices such as the Last Planner System (LPS) and Location-Based Management System (LBMS), emphasising the strategic use of technology for reliable planning and stable production flows. Visual management tools, designed to engage human senses, can enhance the learning curve and situational awareness, increasing understanding of task requirements (Tezel et al. 2016).

Key metrics like Percent Plan Complete (PPC) from LPS can foster a proactive problem-solving culture and instil a sense of ownership among individuals responsible for the work, achieved through formalised discussions during LPS sessions rooted in the action language perspective (Neve & Wandahl, 2018). Integrating daily management with condition monitoring technologies, such as IoT sensors, enhances project-specific knowledge and facilitates the transfer of expertise to future projects, promoting continuous improvement and knowledge dissemination (Alhava et al., 2019; Igwe et al., 2022).

4.3. Methodology

In the initial phase of our study, a causal loop diagram (CLD) was constructed based on extensive literature about the detection, analysis, and elimination of making-do (MD) waste. System Dynamics (SD) methodology, as elucidated by Love et al. (1999), is pivotal in comprehending the intricate interplay between elements within a system. Modelling tools, such as those described by Rodrigues & Bowers (1996), serve as indispensable instruments for pinpointing variables requiring refinement to mitigate waste. The modelling process, while iterative, follows a sequential pattern and necessitates adherence to specific criteria: offering a holistic view of phenomena, establishing causal relationships, and delving into behavioural explanations. CLDs, as per Love and Li (1999), graphically illustrate the direction and

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nature of causality among major factors, empowering professionals to gain profound insights into rework issues and develop preventive strategies for enhanced project performance. As (Love & Li, 2000b) outlined, incorporating feedback control mechanisms augments the structural framework for model construction and aids in selecting pertinent information for informed decision-making. Feedback processes in CLDs manifest as the interplay of positive and negative effects of decisions, providing proactive measures for reducing iterative cycles (Lee et al., 2003). As Lyneis et al. (2001) noted, feedback loops within systems significantly impact project complexity and influence system stability, aligning with Sterman's (2000) perspective. Closed feedback loops, reinforcing (R) or balancing (B), generate accelerating divergent or goal-seeking behaviour. Qualitative studies, complemented by a combination of literature and expert review, identify system variables and establish qualitative relationships, as observed by Black and Repenning. However, expert insights alone are insufficient; data integration is imperative, as (Sterman, 2000) emphasised. This multidimensional approach forms the foundation for understanding and mitigating MD waste in construction projects.

4.3.1. Data Collection

This section expands the waste analysis presented in section 2.5.1, which provides a comprehensive examination of construction waste in a general context; this chapter extends this inquiry by conducting an additional review focused on MD waste.

4.3.2. Data Analysis

The author examined all the cited documents, discerning the relationships (i) among construction wastes from a comprehensive perspective and (ii) conducting a detailed analysis elucidating the intricate interconnections among variables related to MD practices. Subsequently, interviews with experts were conducted to evaluate these relationships, allowing the interviewees to critically assess and validate the findings for accuracy. These reviews often prompted interviewees to contribute additional valuable data. Enabling the study participants to engage in the review process counteracts some inherent biases commonly associated with retrospective interviews.

While the recollections of individual participants typically provided insight into specific aspects of the overall narrative, the interviews comprehensively reviewed the entire case, often uncovering nuances and issues that had not been apparent during the original interviews. In cases where discrepancies or challenges to the narratives emerged, these were meticulously addressed through a rigorous examination of archival data or by conducting additional interviews, ensuring the accuracy and reliability of the study's findings.

4.4. Results

Figure 4-3 exhibits the casual structure of Making-Do waste and how it impacts other variables in construction projects. The casual loops are divided into resource flow across locations, material waste loop, final waste loop, the role of constraints analysis, the impact of overtime, enhancing information flow, the effects of BIM on MD, rework loop, the impact of quality on variability and safety, the effect of defects and design changes loop (Karaz & Teixeira, 2023c).

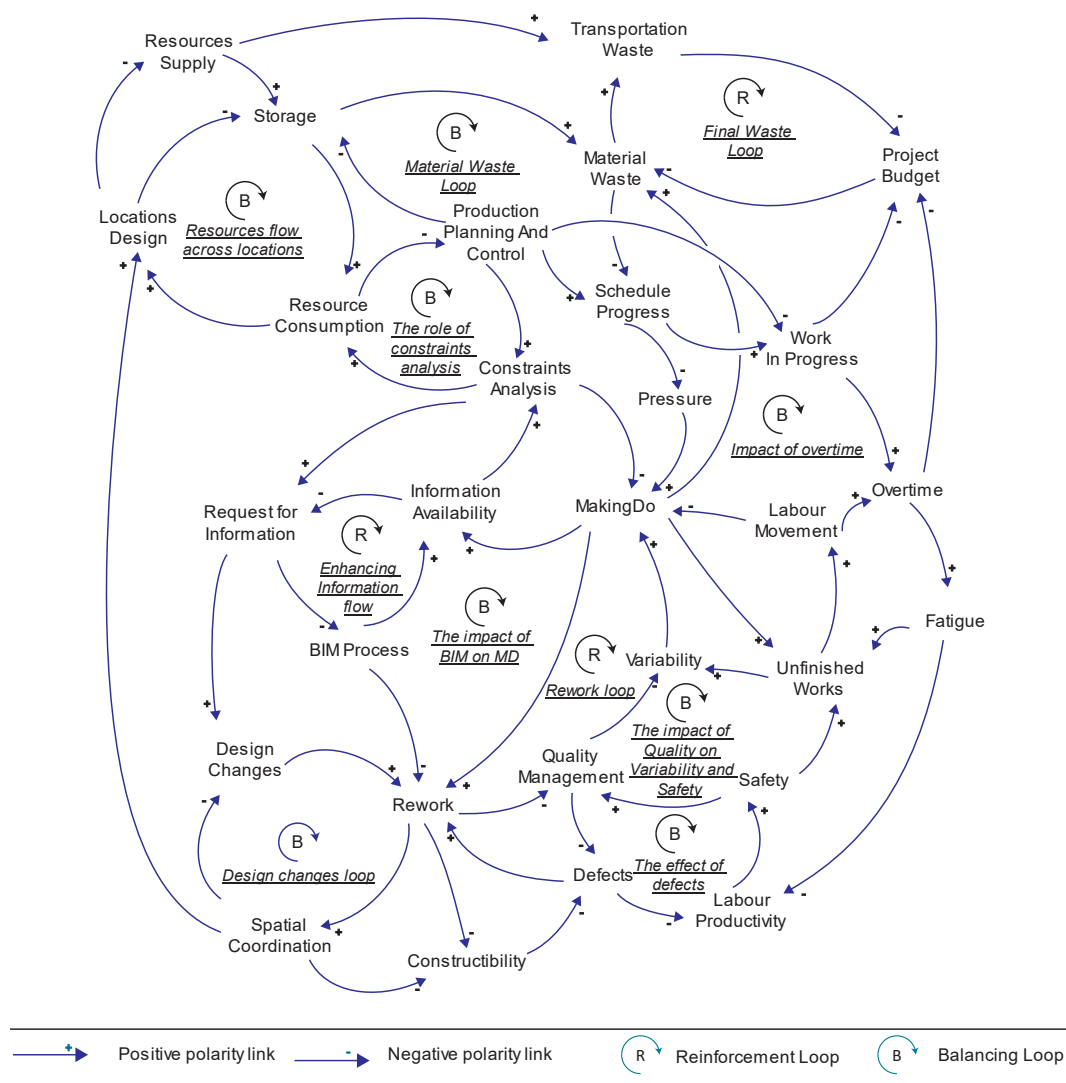


Figure 4-3– Casual Loop Diagram illustrates the structural relationships with prerequisites, MD categories, and impacts.

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Loop R1 highlights the effect of material delivery and site layout planning on the storage, where inventory is a temporary facility that should be planned in the site layout design. The more frequently delivered materials, the more inventory on site is needed when the resource consumption does not meet the delivery rate. Additionally, the more parts are offered, the more complex inventory management is required to reduce inventory accumulation. Loop B2 concerns material waste as an outcome of damaged materials due to storage and movement, excess inventory, and rework. Other causes of material waste indirectly arise from Production Planning and Control (PP&C), such as improper allocation of materials, poor site layout plans, damage during transportation (as shown in Loop R4), poor handling and inappropriate material staging, among others (For more about material waste, check (Formoso et al., 2002)). In loops B1 and R3, labour movement across physical locations is affected by material delivery, the route and site layout design, and planned activities by PP&C. Information about labour routes across the physical locations can be scheduled and controlled through PP&C with the aid of BIM to obtain quantities and perform geometrical analyses of the site layout.

In loop R2, the PP&C actions about work are streamlined from collaborative efforts to prepare work to be structured, sized, sequenced, scheduled, communicated, and controlled, which appears to play a central role in the CLD PP&C is essential for releasing pull signals for the whole production system about crews' resources, production progress, resource consumption, production rates, constraints, and others (as shown in Appendix C). LPS and LBMS can provide this kind of information, which can be considered a real-life data generator about the production system, which helps stakeholders streamline informed decisions about production instead of traditional ad-hoc methods. A proper PP&C system should consider the role of variability in the production system (e.g., the parade of trades), where work chunks should be sequenced, and handoffs between trades should be negotiated and harmonised to prevent starvation or overproduction of planned tasks. PP&C must also provide proactive measures to eliminate the root causes of cascading delays (i.e., interference between the trades in tasks or locations can cause flow interruptions).

The impact of information availability is a prerequisite for PP&C functions, and this variable limits the likelihood of MD emergence and request for information (RFI) (as shown in Loops R14 and R6). A well-defined BIM execution plan should match the Level of Development (LOD) with PP&C details. Information availability variables can be streamlined through tracking and tracing technologies such as indoor positioning, cloud points, and Internet of Things (IoT) techs. These provide real-time control for

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the construction site conditions that can be connected to the BIM process for further visualisation and analysis steps.

Several policies could be applied to regulate the effect of material delivery on project performance. On the site, measures of PP&C associated with planned site layout planning (SLP) were inserted (Cheng et al., 2015). These functions send 'pull' signals for materials to be timely ordered and delivered under the just-in-time (JIT) concept. In the PP&C, the materials should be quantified and allocated before execution. Thus, in any process that commences without the requisite materials, a making-do waste arises, responsible for other wastes such as Work-In-Progress (WIP) and unfinished works, and hinders labourers' productivity. Another waste not communicated in Figure 4-3 is substitution waste, a phenomenon that urges substituting unavailable materials with other materials to meet scheduled deadlines; this waste is similar to making do but hinders productivity due to reworks and defects.

The material delivery also impacts the reliability of production planning and control (e.g., when the required materials are not available when the planned work is released, a making-do effect could be raised, which can snowball to the emergence of rework and defects). The role of SLP (site layout planning) is necessary to coordinate physical locations between the demand of the production system and temporary facilities, delivered materials, crew movements, machine setups, and truck traffic.

BIM processes positively reduce design changes, variability, rework, and RFIs (Dave & Sacks, 2020), as shown in Loops R11, R12, and B4. BIM functionalities such as quantity-take-off, 4D planning, visualisations, clash detection, and interoperability are available in commercial software, bringing valuable information control to the PP&C systems. Actual interaction between BIM functionalities and lean-based PP&C is not mature. The literature actively proposed different prototypes, but a real impact on waste elimination has not been presented yet. However, the potential effects of BIM functionalities on waste reduction are evident even on final wastes such as rework, material waste, and capital waste.

B3, R9, and R10 are concerned with quality management in controlling variability using quality control charts and continuous improvement methodology based on the PDCA cycle (Deming, 1982). Construction variability is the primary source of product defects and process discontinuity, leading to reworks, poor productivity, capital waste, and cascading delays. Loop R7 illustrates the causality of Making Do with WIP and unfinished works. The impact can be explained by working on activities without its prerequisites (e.g., trades that focus on local optimisation are reluctant to pick the most accessible available work packages at the beginning, "a low-hanging fruit phenomenon", crews move to open spaces until a problem appears, leave unfinished work behind them and prevents WIP to be progressed.

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Eventually, this phenomenon led to interruptions in workflow and interference with other trades' schedules, leaving labourers to wait until the problem is resolved, where overtime strategy would be a solution to compensate for the delay, which can lead to labour fatigue and labour productivity to be negatively impacted (Loop R8). Again, the impact of making-do waste is complex and cannot be modelled in a unidirectional causality link (Formoso et al., 2020), which contradicts CLD principles (As shown in loops R7 and R8, the link between making-do and unfinished-works is bidirectional). Thus, further investigation is needed to explore intermediate variables between making-do and other wastes.

4.5. Conclusions

Despite the extensive body of literature addressing the causes of Making-Do (MD) waste, a noticeable dearth of studies focus on developing planning and control strategies to identify and mitigate MD waste effectively. The existing research primarily revolves around quantifying MD waste and exploring the relationships between its causes and consequences (Amaral et al., 2022; Dos Santos et al., 2020; Formoso et al., 2011; Leão et al., 2014). This observation highlights a significant knowledge gap, indicating the absence of an established framework to aid production planners and trade teams in detecting, estimating, and eliminating MD waste from their construction project processes, cultures, and practices.

This chapter analysed the theoretical foundations of Making-Do, delving into its root causes, detection methods, and specific characteristics. The exploration concluded by creating a causal loop diagram connecting prerequisites, MD causes, MD categories, and impacts. Recognising the critical importance of mitigating the adverse effects of MD waste, this chapter is dedicated to bridging this knowledge gap by revealing the causal structure of MD in construction projects. A generic causal loop diagram connects the dots between production planning and control, quality management, harnessing information technology, and social factor empowerment.

Based on the built CLD through this chapter, the subsequent chapter aims to simulate the impacts of effective methodologies, including the Last Planner System, Location-Based Management, and Building Information Modelling (BIM) on MD waste, within a comprehensive policy framework. This framework is designed to proactively minimise the impact of MD waste long before the execution phase, offering a promising approach to enhance both lean and non-lean project management practices.

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This chapter presents the results of a survey to investigate the implementation level of Lean Construction and BIM in the Portuguese construction industry. To achieve this, it estimates the levels of awareness of "making-do" practices among participants and identifies the primary group of stakeholders who support such development. In addition, respondents were given the chance to rank a set of mitigative strategies of MD, which were collected through the qualitative data analysis in Chapter 4.

5. Surveying LPS-BIM strategies for MD mitigation

5.1. Introduction

The significance of both the Last Planner System (LPS) and Building Information Model (BIM) is widely acknowledged in addressing the shortcomings of production planning and control that led to Making-Do (MD); however, the current policies lack validation. Accordingly, this chapter assesses the stakeholders' expectations about LPS and BIM for MD mitigation strategies from the existing literature review that used thematic analysis, a qualitative data analysis technique in Figure 5-1. The following step was embedding the identified factors in a questionnaire survey to explore new terms applied to describe MD practice in the construction industry and to classify the aspects of the developed criteria for evaluating LPS and BIM methods to control MD waste. The survey revealed three principal groups of factors: "BIM-based collaboration for constraint analysis," "Medium-term and Short-term MD analysis," and "Enterprise learning and adaptation," which includes, but is not limited to, components like "improved documentation for MD cases" and "Dynamic reports for MD and constraint analytics." Proper understanding and consideration of these factors are significant in addressing the stakeholders' expectations regarding applying LPS. Along with the expectations of relevant industry practitioners, an LPS-BIM framework for MD mitigation policy was built, including the technological and industrial needs for planning and control of the production and the MD mitigation.

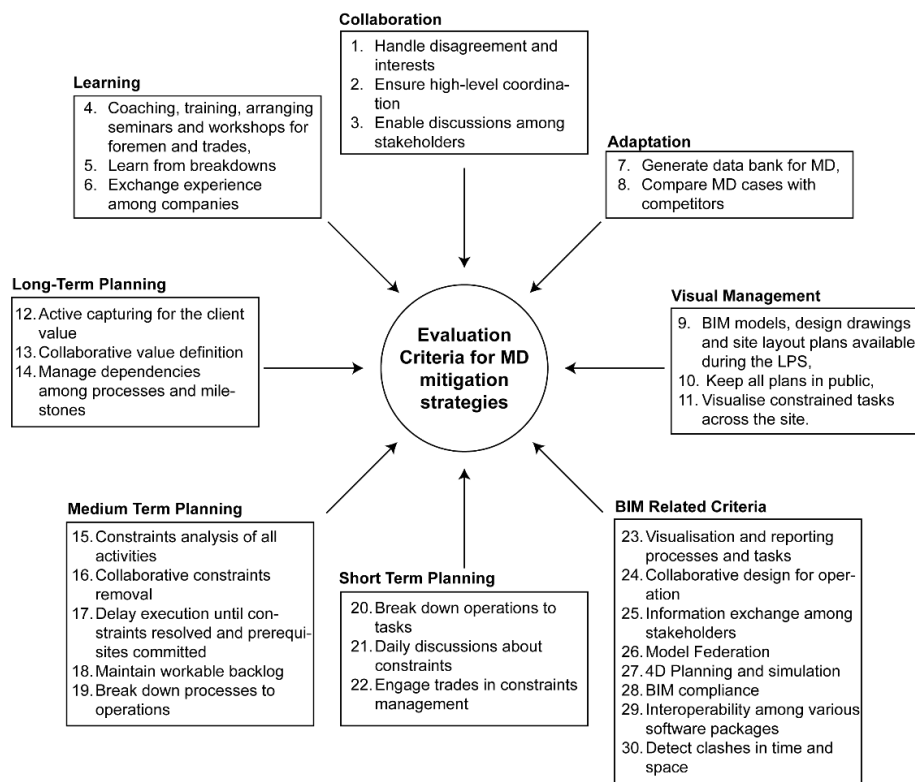


Figure 5-1 - A Framework of Policy to Improve the Performance of MD Mitigation Models.

5.2. In-depth exploration of the critical factors that mitigate MD through LPS and BIM

This section will comprehensively examine the dynamic variables associated with the LPS and BIM to limit MD practices and their adverse consequences. Considering the intersections of these variables, the discussion will explore the social factors inherent in the LPS in terms of collaboration and adaptation. Subsequently, this section will discuss the technical components of the LPS, including aspects such as visual management and medium short-term planning. Finally, the functionality of BIM will be explained within this context.

5.2.1 Collaboration

The dynamic variable “Collaboration” constitutes an essential aspect of the LPS. Without collaboration, the efficacy of the LPS will remain limited, and its outcomes will be less promising (Ballard,2020), as it becomes challenging to foster trust and commitment among trades without a collaborative approach to implementing the LPS. This variable underscores the radical innovation brought about by the LPS, particularly in its social dimension. Collaboration facilitates deployment planning and control responsibilities throughout the project organisation and focuses on reliable promises between interdependent players as the key to the successful application of the LPS. Successful implementation of a collaborative LPS includes multiplication of the following parameters:

- **Handling conflicts among various stakeholders:** Addressing conflicts among diverse stakeholders is a critical metric that seeks to gauge the extent of project management's exertion in harmonising interests across multiple sectors. It also encompasses resolving disputes about responsibility for constraints and the mechanisms employed for their removal.
- **Enabling discussions:** Facilitating discussions is a crucial dimension that assesses how project management encourages dialogue among relevant parties during the planning phase and the resolution of their tasks within lookahead and make-ready planning sessions.
- **Ensuring a high level of coordination:** This input specifies the percentage of coordination implemented during Last Planner System (LPS) sessions.
- **Engagement level in constraints analysis:** This parameter enables users to designate the degree of involvement for each trade in the constraints analysis process. A heightened level of engagement can result in more reliable plans and a reduction in MD practices when constraints are removed correctly and collaboratively.

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- **Measure plan performance:** This parameter is dedicated to assessing the reliability of measurements for planning performance. It examines the potential for missing data or errors in reporting the PPC metric, including the possibility of overestimating PPC.

5.2.2 Adaptation

This dynamic variable assesses the level of adaptation within LPS practices, aimed at fostering a more common or shared understanding among the project parties while applying LPS and addressing root causes of resistance to changes during the LPS implementation (Rooke, 2020). The adaptation variable addresses the root causes of resistance to change by transforming organisational values, encouraging local adjustments, and enhancing individual capabilities through further training and education in lean construction philosophy and LPS principles; additionally, as part of social LPS, the adaptation variable endeavours to mitigate MD practices by generating data banks in computerised forms through active data collection on MD incidents. This process involves the development of meaningful language to store, analyse and organise the ontology of MD. The adaptation variable is the multiplication of the following parameters:

- **Local adjustments to organisations:** Local adjustments to organisational practices encompass the modifications made to accommodate the Last Planner System in alignment with the organisation's culture, resources, projects, priorities, goals, and visions. These adjustments are tailored to integrate seamlessly with the network of stakeholders associated with the organisation.
- **Coaching and training:** Evaluation of coaching and training effectiveness pertains to the level of instruction provided to superintendents and crew leaders in collaborative pull planning. It also encompasses assessing how planners prepare for and sustain the implementation of the LPS.
- **Generate data bank about LPS metrics and MD incident records.:** Timely data collection is imperative for monitoring identified MD incidents and their resolutions. The data repository for MD incidents should comprehensively detail each occurrence, including its unique identifier (ID), timestamps for the incident history, MD category, associated constraints, root cause analysis, involved trades, location, process name, operation details, task specifics, MD impact and any countermeasures employed if corrections were made.
- **Exchange experiences with other enterprises:** Exchanging experiences provides a valuable opportunity to share insights and learnings. Through disseminating successful and unsuccessful stories, enterprises can derive a collection of strategies acquired through experience, aiding in mitigating adverse MD occurrences in their projects. This collaborative

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approach enables the transfer of knowledge and the cultivation of a more informed and resilient project management framework.

- **Compare MD records and experience with other enterprises:** Analysing MD records and experiences compared with other enterprises offers a competitive advantage, allowing companies to benchmark their waste reduction efforts. This comparative assessment provides valuable insights into industry practices, enabling the identification of best practices and areas for improvement in managing and minimising MDs.

5.2.3 Visual Management

One of the components of soft Lean Construction tools involves educating individuals to recognise waste and flow within their projects. This concept, known as “learning to see,” aligns with the principles concept of visual management, which employs different tools that target the human five senses to increase the transparency of the construction process and reveal wastes (Tezel & Aziz, 2017). In this dynamic system, this variable is characterised by the multiplication of three parameters, as outlined below:

- **Communicate instructional and actionable information.:** Communicate the traditional list of wastes around the site clearly and concisely. Also, infographics about the causes of MD and the possible consequences should be distributed.
- **Keep all plans public:** All plans at all levels of the LPS hierarchy should be shared and seen with involved parties. This step increases situational awareness regarding task constraints, which can prevent possible MD.
- **BIM models available during LPS sessions:** In LPS sessions, it is imperative to employ the most up-to-date BIM models to facilitate the essential information required for task planning and execution. It is recommended that functional analysis, quantity take-off schedules, 4D BIM information, and task-specific attributed data be shared with the BIM database. This collaborative approach enhances the effectiveness of planning sessions.

5.2.4 Lookahead Planning

This subsection transitions to the technical aspects of the LPS, which focuses on lookahead planning, positioned between long-term and short-term planning. This stage of the LPS hierarchy entails breaking down project phases and milestones into operational tasks, as outlined in Chapter 2. At this stage, the fundamental function of the LPS lies in the constraints analysis, a process hypothesised by the literature

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that significantly impacts tackling MD when it is executed successfully. A collaborative design for operations emerges as another pivotal function of LPS, enhancing visual management as elucidated in subsection 5.1.4 and leveraging collaboration parameters in subsection 5.1.1. The variable Lookahead planning comprises the following constituents:

- **Constraints management:** The core function of the LPS is constraints analysis, which can be performed at each level of planning. For example, the master schedule is constrained by cost, time, quality, environment, and social factors in a broader view. In pull planning, the constraints are interdependent among processes, and conditions of satisfaction for each process should be screened before moving towards Lookahead planning.
- **Break down work packages into actionable details:** Break down projects into phases and phases into milestones. Within milestones, define processes, processes into operations, operations into tasks, and tasks into elemental motions. The LPS hierarchy must be followed, particularly for highly uncertain critical tasks. MD practices should be classified within the publicly discussed LPS hierarchy during LPS sessions.
- **Collaborative design for operations:** Collaborative operation design is advisable for exploring various scenarios of constraints and anticipating potential issues MD before execution. Methods recommended in the literature include virtual prototyping techniques (such as BIM simulation DES), first-run studies, and physical prototyping.

5.2.5 Weekly, Bi-weekly, and Daily Planning

This subsection describes the parameters that comprise short-term planning within the LPS. This operational stage of the LPS involves aligning managerial directives with weekly, bi-weekly, and daily feedback from trades. It entails providing feedback on workable backlogs, engaging individuals in daily constraint discovery and removal, making commitments to work, facilitating constraint removal, and monitoring work progress to calculate the Plan Percent Complete (PPC). The multiplication of the following parameters formulates the short-term planning variable:

- **Daily huddle meetings:** This parameter specifies the percentage of daily meetings between workers and superintendents. These meetings involve discussions on planned and completed tasks, addressing technical task execution details. Workers also directly report the daily work output from the previous day, highlighting any encountered constraints during execution. Furthermore, white-collar personnel are included in these meetings, especially during Gemba walks.

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- **Maintain workable backlog:** The workable backlog is a crucial parameter as it ensures the availability of work for execution ahead of time, preventing engagement with constrained tasks. Tasks located in this backlog are more likely to be free from constraints, or their constraints are less uncertain. Additionally, it aids in classifying non-workable tasks, prompting individuals to inquire about their constraints and attempt to resolve them so they can be included in this workable backlog later.
- **Engagement level in constraints analysis:** This parameter enables users to designate the degree of involvement for each trade in the constraints analysis process. A heightened level of engagement can result in more reliable plans and a reduction in MD practices when constraints are removed correctly and collaboratively.
- **Daily discussion of constraints:** The more frequently the constraints are discussed, the more they are understood and removed. A daily conversation is recommended to achieve a higher level of collaboration in removing constraints and preventing MDs.

5.2.6 BIM Functionalities

The existing BIM functionalities vary widely based on the purpose of use, according to (ISO, 2018). For MD mitigation, the following functionalities are explained:

- **Add MD attribute to BIMs:** Facilitating the incorporation of MD and constraints information within BIM construction management and authoring software is essential. This parameter measures the percentage of MD information a project team integrates into the parametric BIM model.
- **Utilise 4D BIM for the tasks at the last planner hierarchy:** This parameter quantifies the percentage of planning details incorporated into the 4D BIM. It is advisable to enhance the level of 4D planning in alignment with the LPS hierarchy.
- **Apply clash detection analysis to discover spatial constraints:** This value represents the percentage of applied clash detection across a project. This BIM functionality is recommended to prevent spatial clashes between the works of different trades. Additionally, it can assist decision-makers in determining the sequencing among operations.
- **Utilising colour-coded visualisation to represent task status:** This parameter denotes the percentage of visualisation utilised for tracking task status in response to Andon signals. It encompasses embedded types of constraints associated with tasks and reported MD issues. Additionally, this parameter reports visualised information used by white-collar personnel for data collection and offer guidance on task execution or problem resolution.

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- **Online communication tools using BIM cloud services:** This parameter specifies the percentage of communications performed over BIM cloud services to exchange production information on developed BIM models by design teams with site management, crew leaders, and crews.

5.3. Research Methodology

A comprehensive literature review identified 30 variables related to using BIM and LPS for MD mitigation. These variables were subsequently structured into a questionnaire survey, and a pilot study was conducted to refine the questionnaire before its distribution to the intended respondents. The pilot study involved five PhD students in Civil Engineering, whose feedback informed the final version of the questionnaire presented in Appendix A.

5.3.1 Questionnaire Design

The questionnaire survey commenced with a pilot study employing a preliminary questionnaire containing a compiled list of LPS and BIM strategies for MD mitigation. This initial phase assessed questionnaire relevance, length, complexity, and layout. Participants for the pilot study were selected from two Portuguese universities and comprised PhD students specializing in construction management and BIM research. Feedback from the pilot study participants was instrumental in refining the final questionnaire.

The final questionnaire survey comprises the following three sections:

SURVEY COVER LETTER – This section explains the purpose of the survey, provides a definition of MD practice, and elaborates on examples from the literature. The respondents were informed that the data collected would be used solely for research purposes to encourage a high response rate. Likewise, the respondents were assured that the confidentiality of all individuals' responses would be maintained.

SECTION A: DEMOGRAPHIC OF THE RESPONDENTS – This section captures demographic information about respondents. The respondents were asked to indicate their experience level, education level, and designation. This section would enable the researcher to identify the respondents' roles within which industry.

SECTION B: LEAN AND BIM EDUCATION AND IMPLEMENTATION – This section captures whether the respondents have been in training or a BIM and Lean Construction

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course. The respondents indicated their years of experience in Lean construction, BIM, and the LPS.

SECTION C: MD KNOWLEDGE AND EXPERIENCE – This questionnaire section included questions about MD terminology and decision-making in the context of MDs to identify the main categories of actors involved in such decision-making.

SECTION D: BODY OF QUESTIONNAIRE – This section allows respondents to rate the LPS and BIM strategies for MD mitigation. The respondents were asked to consider each factor relevant to their perceived competence and to rank their importance on a five-point Likert scale ranging from 1 (not Important) to 5 (most Important).

The survey respondents were required to indicate the importance of the variables on a five-point Likert scale, where one represents “not important” and five means “most important.” The questionnaire was then developed into a web-based (GoogleForms) to encourage completion and reduce potential errors to aid data analysis. By employing a search for construction management practitioners in the LinkedIn database, 336 respondents were randomly selected for the survey (including project managers, superintendents, estimators, schedulers, field engineers, quality control managers, safety coordinators, document control technicians, bid coordinators, procurement specialists, clients, designers, and students. Figure 5-1 shows the demographic distribution of the respondents. The survey's response rate was 21.82%, indicating that only Seventy-Two (72) completed questionnaires were fully submitted. As part of the data inspection process, returned questionnaires that were deemed invalid were eliminated, 2 of the submitted questionnaires were incomplete, discarded, or those with identical or regular answers, and those that did not adhere to the rules of the questionnaire. Thus, only 72 usable responses were found for analyses (21.82%). Rigorous screening and verification of the questionnaire's quality ensures that an effective questionnaire possesses high reference and analytical value. The survey questions were structured using three answering methods: singular and multiple selective methods and rating scales.

5.3.2 Respondents Profile Assessment

This subsection describes the analysis results for the respondents' profiles. The distribution of respondents' years of professional experience exhibits a relatively uniform pattern (See Table 5-1). Specifically, 24.7% of respondents reported 0-5 years of experience, while 24.9% indicated an experience range of 11-15 years. Additionally, 21.9% of respondents possessed 6-10 years of

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professional experience, and those with 16-25 years constituted 12.3%. Professionals with over 25 years of experience in construction projects represented the smallest cohort, with a response rate of 16.4%.

Table 5-1 – Demographic characteristics of the survey respondents

Data from the questionnaire survey	Sample size
The total questionnaire was sent out.	336
Total submitted responses	74 (22.42%)
Discarded responses	2
Total number of usable responses	72 (21.82%)
<i>Years of experience in the construction industry</i>	
0-5 years	23.61%
6-10 years	22.22%
11-15 years	19.44%
16-20 years	8.33%
Above 20 years	12.50%

Figure 5-2 illustrates the distribution of educational qualifications among survey respondents. Most respondents, 59.72%, hold master's degrees, followed by 25.00% with bachelor's degrees. Those with doctoral degrees make up 8.33%, and the remaining 6.94% have various other qualifications, including a high school diploma or equivalent, some college but no degree, and an associate degree.

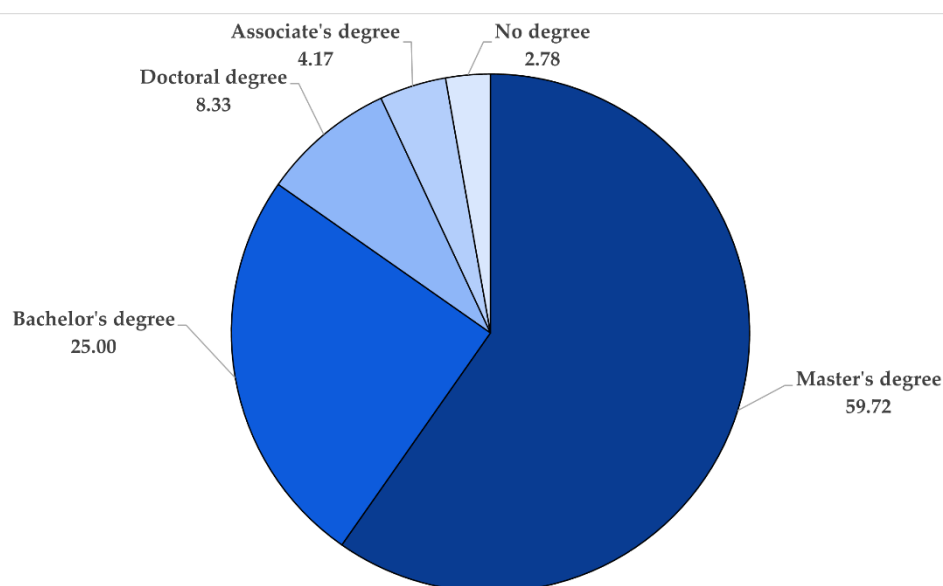


Figure 5-2 – Educational attainment among the survey participants.

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Figure 5-3 depicts the distribution of job titles among the respondents. Project managers and field engineers represent the most prominent groups at 14.29% and 12.86%, respectively. Similarly, designers represent a significant presence, constituting 10.00% of the respondents. Superintendents comprise 7.14%, and Bid Coordinators and Schedulers account for 5.71% equally. Safety coordinators comprise 4.29% of the population, and researchers, PhD students, board members, BIM coordinators, CEOs, and quality control managers account for 2.86% of the total.

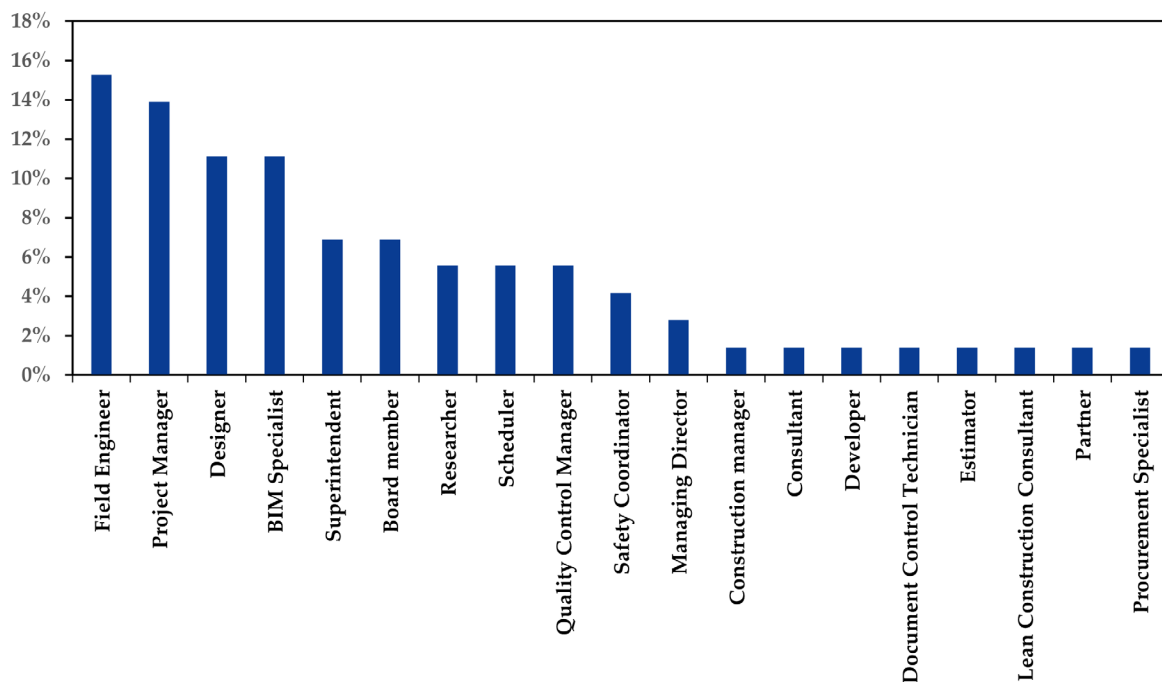


Figure 5-3 – Occupational roles within the respondent group.

The data in Figure 5-4 reflects the respondents' background in Lean Construction, the Last Planner System, and BIM by asking if they ever attended courses, training, workshops, or reading. Most respondents lack formal education in Lean Construction, with 54.17% indicating no such education; the case is not the same with BIM education, which forms 65.25% of the respondents who have received some formal education or training.

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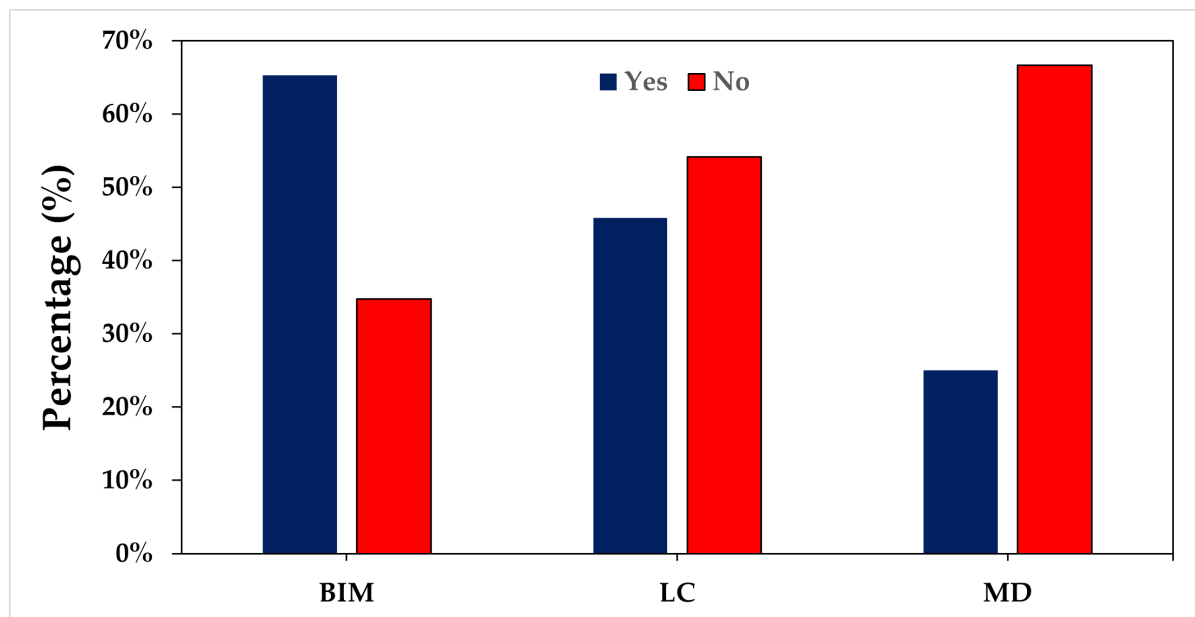


Figure 5-4 – The percentage of Lean and BIM Education and Training among the Respondents

As shown in Figure 5-5, the application of Lean Construction and the Last Planner System varies, with a significant percentage indicating no use 63.89% and 70.83%, respectively. Meanwhile, 18.06% of the participants experienced the Lean construction philosophy in their workflows for 1-5 years, making up 15.28% of the participants who used the LPS for production planning and control in their enterprises for the same period. However, BIM education and application exhibit higher involvement, with 41.67% having BIM education and 26.39 % applying BIM for 1-5 years. The findings provide insights into the respondents' knowledge and experience levels in these construction methodologies and technologies.

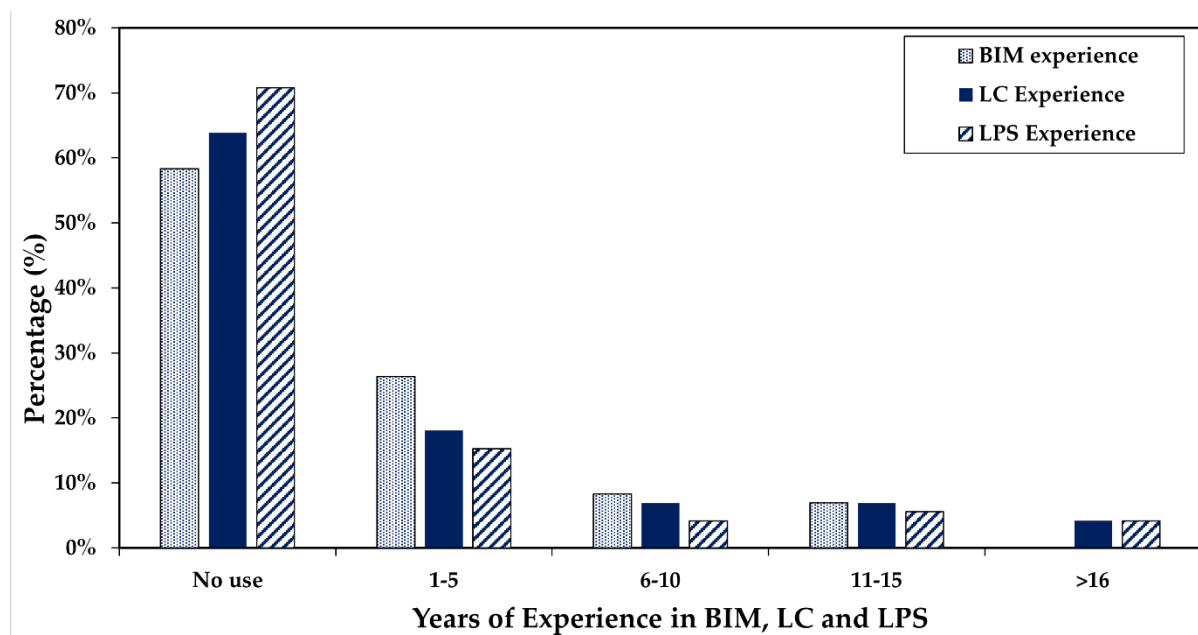


Figure 5-5 – The Respondents Experience in Lean and BIM (years)

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5.3.3 Analysis of the perception and expectation of the respondents about MD

Figure 5-6 assesses the extent of knowledge regarding MD waste among Portuguese construction professionals. Despite the term's inception in 2004, 67.9% of respondents demonstrate a lack of familiarity or utilisation of this terminology or analogous terms in their professional capacities. Nevertheless, 14.3% of respondents indicated some level of awareness, while an additional 17.8% incorporated related concepts such as task requirements, delivery checklists, lists of work security, quality checklists, and constraints checklists into their understanding.

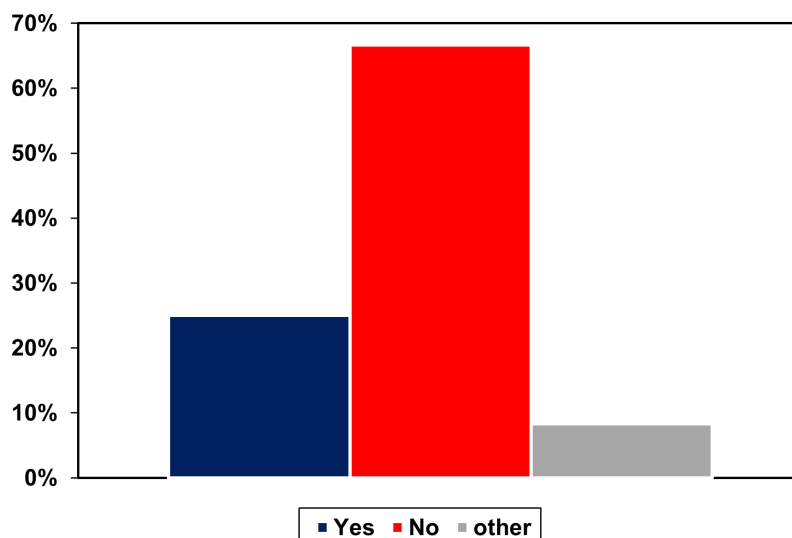


Figure 5-6 – The knowledge and use of Making-Do terminology and similar concepts.

Figure 5-7 presents an estimation that respondents were asked to fill out, which reflects the percentage of MD expected in the construction workflows. 18.06% of respondents see that their workflows are free of MD practices, 23.61% estimated that MD constitutes 25% of their production, 34.72% projected MD practices infect half of their workflows, 22.22% confirmed that MD is presented in more than 75% of their production. This estimation is a rough quantification of MD and might lack clarity or formal measurement, but it reflects that once the MD concept was introduced to the participants, they perceived that MD waste is an integral part of their decisions across the construction lifecycle.

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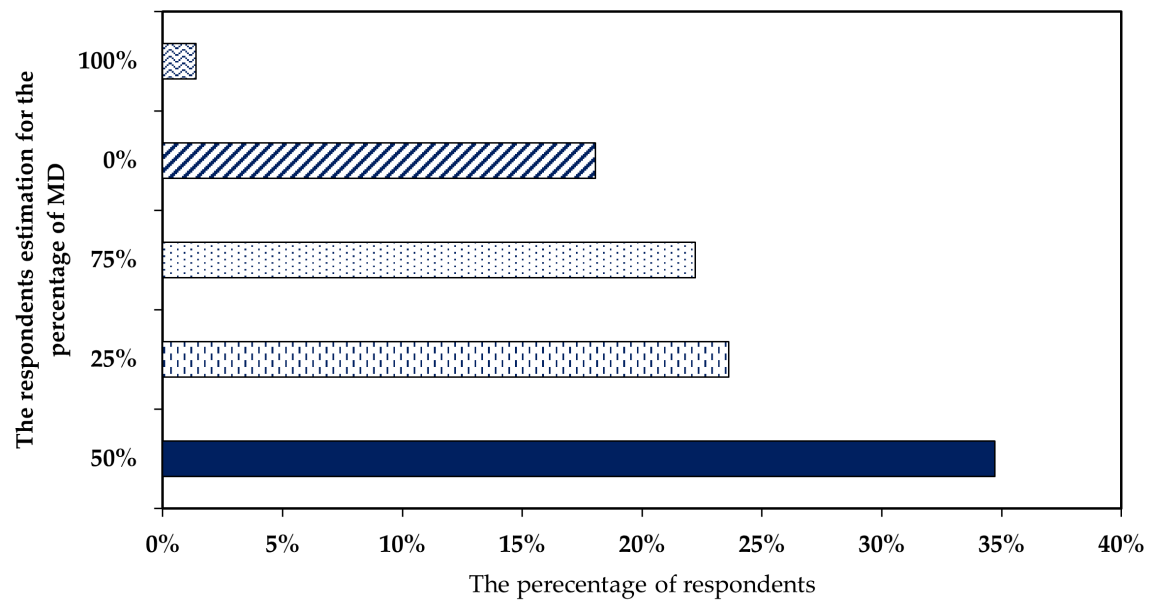


Figure 5-7 – Estimated Percentage of MD in construction workflows according to the respondents.

Figure 5-8 reveals the respondents' perspectives regarding the primary stakeholders involved in MD within their workflows. The findings indicate that speciality trades and project managers are considered the most significant contributors to MD decisions, accounting for 27% and 17%, respectively. Designers follow closely with 66.2%, clients at 63.5%, project managers at 62.2%, regulators at 48.6%, and consultants at 44.6%. The substantial representation of trade crews in the responses aligns with the data gathered in the case study presented in Chapter 5.

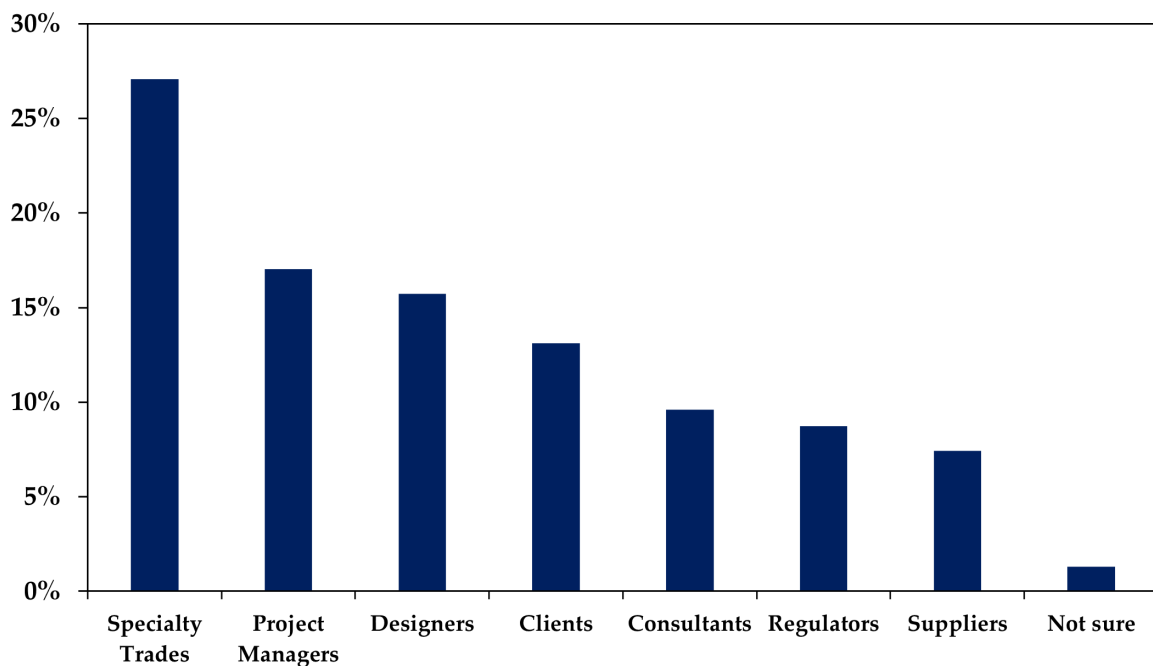


Figure 5-8: Examination of respondents' perspectives on the entities accountable for Making-Do (MD) waste generation.

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5.4. Results

5.4.1 Reliability analysis

Reliability analysis assessed the internal consistency of the variables related to using BIM and LPS to mitigate MD practices in construction projects. A total of 25 variables were tested if they are, and the Likert scale consistently reflects the construct of the study set out to measure. Accordingly, Cronbach's alpha coefficient of reliability (α) was calculated for the variables using Equation 5.1.

$$\alpha = \frac{N}{N-1} \left(1 - \frac{\sum \sigma_i^2}{\sigma_T^2} \right) \quad \text{Equation 5-1}$$

In this context, N represents the total number of questions. Each question has a score variance denoted as σ_i where i ranges from 1 to n. The overall test score's total variance, not in percentage form, is represented by the σ_T . Cronbach's alpha α which has a value from 0 to 1, and the higher the value of (α), the greater the internal consistency of data (Field, 2005). It is generally believed that a value of $\alpha = 0.7$ is acceptable, and $\alpha > 0.8$ depicts good internal consistency. The calculated α for this study is 0.9475, demonstrating an excellent internal consistency. The 25 variables were then ranked using the descriptive statistical mean as the ratio of importance. The results of the reliability analysis and ranking of the variables are shown in Table 5-2.

Table 5-2 – Reliability analysis table with means and ranking of LPS and BIM strategies for MD mitigation.

No	Variable	Mean	Cronbach's Alpha	Rank
VA24	Identify and resolve time and space clashes using BIM Clash Detection tools.	3.736	0.945	1
VA23	Report task information in alignment with product specifications to ensure accuracy.	3.722	0.945	2
VA25	Facilitate the exchange and communication of Making-Do practices through online BIM models.	3.722	0.944	3
VA22	Utilise 4D planning to visualise constraints and their impact on project timelines.	3.681	0.945	4
VA5	Provide coaching, training, and seminars for superintendents and forepersons.	3.653	0.945	5
VA11	Ensure the availability of BIM models, design drawings, and site layout plans for reference during the implementation of the Last Planner System.	3.611	0.944	6
VA21	Facilitate daily discussions between trades to address constraints and coordinate activities.	3.583	0.945	7
VA2	Ensure high-level coordination among project stakeholders.	3.542	0.946	8

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VA20	Collaboratively design operations using BIM for digital prototyping.	3.486	0.945	9
VA12	Maintain transparency by keeping all plans publicly accessible.	3.472	0.945	10
VA14	Apply constraints analysis proactively to identify and address potential issues as a team.	3.472	0.945	11
VA9	Facilitate knowledge exchange and sharing experiences among different companies.	3.458	0.945	12
VA3	Facilitate discussions to address concerns and foster consensus.	3.444	0.945	13
VA7	Establish a data bank to clarify misconceptions regarding Lean construction, Making-Do, and Last Planner System principles.	3.444	0.946	14
VA1	Handle disagreements and interests effectively to foster collaboration.	3.431	0.947	15
VA6	Process and translate knowledge from experiential learning into actionable insights.	3.403	0.946	16
VA13	Utilise guiding information across digital and physical environments to enhance understanding.	3.403	0.946	17
VA17	Involve stakeholders in constraints management processes to enhance collaboration in Mitigating MD.	3.347	0.944	18
VA8	Learn from past incidents of Making-Do.	3.306	0.946	19
VA16	Encourage stakeholders to communicate and share any constraints that may impede progress.	3.278	0.945	20
VA10	Compare and analyse multiple cases to understand how Making-Do is managed.	3.264	0.946	21
VA4	Adapt local adjustments to align with organizational requirements.	3.181	0.947	22
VA18	Maintain a workable backlog of tasks to prioritize and manage workload effectively.	3.153	0.944	23
VA15	Delay tasks with uncertain constraints to avoid potential disruptions.	2.931	0.947	24
VA19	Break down tasks from processes to operations and further to individual tasks for clarity of management and control.	2.889	0.947	25

The mean ranking reveals that “Identifying and resolving time and space clashes using BIM Clash Detection tools” is the most significant stakeholder expectation of using BIM for MD mitigation. This rank is because the construction industry is long overdue for BIM-Based tools to identify conflicts.

5.4.2 Exploratory Factor Analysis (EFA)

The factor analysis method aims to discover "underlying" structures associated with the variables revealed in the literature. Its goal is to determine the set of dimensions forming variables as the base of their structure, using the reductionist method to substitute them with fewer uncorrelated principal components. The resulting procedures have the added advantage of deleting redundant (highly correlated) variables while at the same time preserving the integrity of the original data. In this research,

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factor analysis was done by Minitab employing principal component analysis (PCA) with oblique rotation (varimax) of 25 variables. PCA was employed for factor extraction, and varimax rotation was used as a rotation procedure. The Kaiser-Meyer-Olkin (KMO) measure for the sampling adequacy got a value of 0.873, which is higher than the recommended threshold of 0.5, while Bartlett's Test of Sphericity resulted in a p-value of 2.45×10^{-104} (less than 0.5) as shown in Table 5-3, suggesting substantial evidence against the null hypothesis of an identity matrix.

Table 5-3 – KMO and Bartlett's Test

Kaiser-Meyer-Olkin of Sampling Adequacy.		0.873
Bartlett's Test of Sphericity	Approx. Chi-Square	1178.643
	df	300
	Sig.	<0.000

That demonstration previously mentioned confirms that this data set is suitable for factor analysis. The PCA results reorganise the list of variables into five factors, which account for the total variance of 67.871%, as shown in Table 5-4. Accordingly, the groups were deduced and categorised based on the assigned variables. The groups include:

- Group A, denoted by Integrated Production and Product Information
- Group B is denoted by Adaptation Towards LPS and MD-free culture.
- Collaborative Commitment towards MD Mitigation denotes Group C
- Group D is denoted by Constraints Analysis with Short and Long-term Planning
- Group E denoted by Active Feedback Mechanisms for MD Incident Resolution

Table 5-4 – Component labelling and corresponding criteria from factor analysis

No	Variable	Eigen Values	% of Variance	Loading Factor
A- Integrated Production and Product Information Management		11.338	45.353%	
VA24	Identify and resolve time and space clashes using BIM Clash Detection tools.			0.767
VA23	Report task information in alignment with product specifications to ensure accuracy.			0.712
VA25	Facilitate the exchange and communication of Making-Do practices through online BIM models.			0.715
VA22	Utilise 4D planning to visualize constraints and their impact on project timelines.			0.803
B- Adaptation Towards LPS and MD-free culture		1.761	7.043%	
VA5	Provide coaching, training, and seminars for superintendents and supervisors.			0.672

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VA6	Process and translate knowledge from experiential learning into actionable insights.		0.715
VA4	Adapt local adjustments to align with organizational requirements.		0.527
VA11	Ensure the availability of BIM models, design drawings, and site layout plans for reference during the implementation of the Last Planner System.		0.655
VA12	Maintain transparency by keeping all plans publicly accessible.		0.739
VA13	Utilise guiding information across digital and physical environments to enhance understanding.		0.511
VA21	Facilitate daily discussions between trades to address constraints and coordinate activities.		0.576
VA19	Break down tasks from processes to operations and further to individual tasks for clarity of management and control.		0.698
VA18	Maintain a workable backlog of tasks to prioritize and manage workload effectively.		0.688
VA15	Delay tasks with uncertain constraints to avoid potential disruptions.		0.759
C- Collaborative Commitment towards MD Mitigation		1.426	5.702%
VA2	Ensure high-level coordination among project stakeholders.		0.743
VA3	Facilitate discussions to address concerns and foster consensus.		0.678
VA1	Handle disagreements and interests effectively to foster collaboration.		0.748
VA20	Collaboratively design operations using BIM for digital prototyping.		0.644
D- Constraints Analysis with Short and Long Terms Planning		1.324	5.297%
VA14	Apply constraints analysis proactively to identify and address potential issues as a team.		0.644
VA17	Involve stakeholders in constraints management processes to enhance collaboration in Mitigating MD.		0.796
VA16	Encourage stakeholders to communicate and share any constraints that may impede progress.		0.738
E- Active Feedback Mechanisms for MD Incident Resolution		1.119	4.476%
VA9	Facilitate knowledge exchange and sharing experiences among different companies.		0.528
VA7	Establish a data bank to clarify misconceptions regarding Lean construction, Making-Do, and Last Planner System principles.		0.512
VA8	Learn from past breakdowns and instances of Making-Do.		0.676
VA10	Compare and analyse multiple cases to understand how Making-Do is managed.		0.724
		16.968	67.871%

5.5. Structural Equation Model (SEM)

Based on SEM, a Confirmatory Factor Analysis (CFA) was implemented in AMOS software to verify the measurement model's validity. The SEM comprises defining the measurement model and the structural model.

5.4.1. Measurement Model Fitness

The measurement model was established using the graphical representation functionality in AMOS 26.0.0. as shown in Figure 5-9. The model comprised four variables, COO, MDK, LPS, and BIM, representing 25 factors loaded on these variables. Similarly, 25 errors were associated with these factors, and measuring these unobserved errors forms the power of SEM, which other multivariate methods cannot measure. The model assumes covariances among all unobserved variables: COO, MDK, LPS, and BIM.

As a composite of CMIN/df, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Residual (RMSEA), and Standardized Root Mean Square Residual (SRMR), these model-fit indices were used for the overall evaluation of the model. Some calculated statistics significantly differed from the established below-standard value defined in previous research (Bagozzi & Yi, 1988; Bentler, 1990; Hu & Bentler, 1998; Schumacker & Lomax, 2004). The four-factor model, comprising COO, MDK, LPS, and BIM, demonstrated some unsatisfactory fit to the data, as indicated by the following fit indices: CFI = 0.786, TLI = 0.762, SRMR = 0.099, and RMSEA = 0.098. However, the satisfactory fit to the data is as follows: CMIN/df = 2.133 and probability level = 0.000 (Table 5-5 includes model-fit indices; please see below for more details)

Table 5-5 – Model fitness measures

Fit indices	Threshold	Obtained value	Evaluation	Source
Probability level	Insignificant	0.000	Passed	(Bagozzi & Yi, 1988)
CMIN/DF	Between 1 and 3	2.133	Excellent	(Schumacker & Lomax, 2004; Ullman & Bentler, 2012)
CFI	>0.95	0.786	Terrible	(Bentler, 1990)
TLI	>0.08	0.762	Terrible	
SRMR	<0.08	0.099	Unacceptable	

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RMSEA	<0.06	0.098	Terrible	(Hu & Bentler, 1998)
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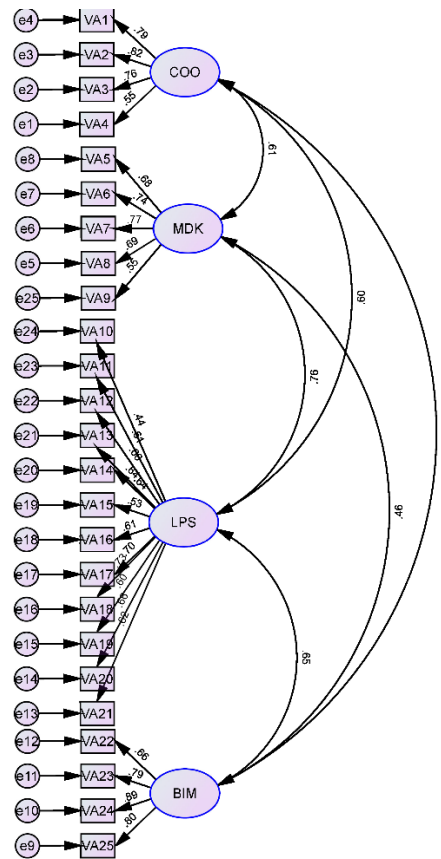


Figure 5-9 – Unadjusted SEM measurement model

The validity test shows that the measurement model requires several modifications. First, by looking at factor loadings for every item, It was found that three items, i.e., VA4, VA10, VAR21, had low factor loadings (VA4 = 0.46, VA10 = 0.45, VA21 = 0.48) which are all less than the accepted threshold of 0.5. Therefore, they were taken out of the study. Second, after looking at the medication indices, several covariances are suggested to be drawn in (BIM: e25 ↔ e24, e25 ↔ e21, e25 ↔ e22, e23 ↔ e22) and (LPS: e11 ↔ e12, e12 ↔ e13, e16 ↔ e17, e17 ↔ e18, e18 ↔ e19, e11 ↔ e19), afterwards another analysis was carried out after running the analysis for the model fitness after modifications for the measurement model. These model-fit indices were used to evaluate the model as a composite of CMIN/df, CFI, TLI, RMSEA, and SRMR. Significantly, the means of all calculated statistics were within the established standard values. The four-factor model, comprising COO, MDK, LPS, and BIM, demonstrated a satisfactory fit to the data, as indicated by the following fit indices: CMIN/df = 1.490, CFI = 0.932, TLI = 0.911, SRMR = 0.08 and RMSEA = 0.065 (Table 5-6 includes model-fit indices; please see below for more details).

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Table 5-6 – Model fitness measures for the adjusted measurement model

Fit indices	Threshold	Obtained value	Evaluation
Probability level	Insignificant	0.000	Passed
CMIN/DF	Between 1 and 3	2.133	Excellent
CFI	>0.95	0.946	Acceptable
TLI	>0.90	0.932	Excellent
SRMR	<0.08	0.063	Excellent
RMSEA	<0.06	0.060	Acceptable

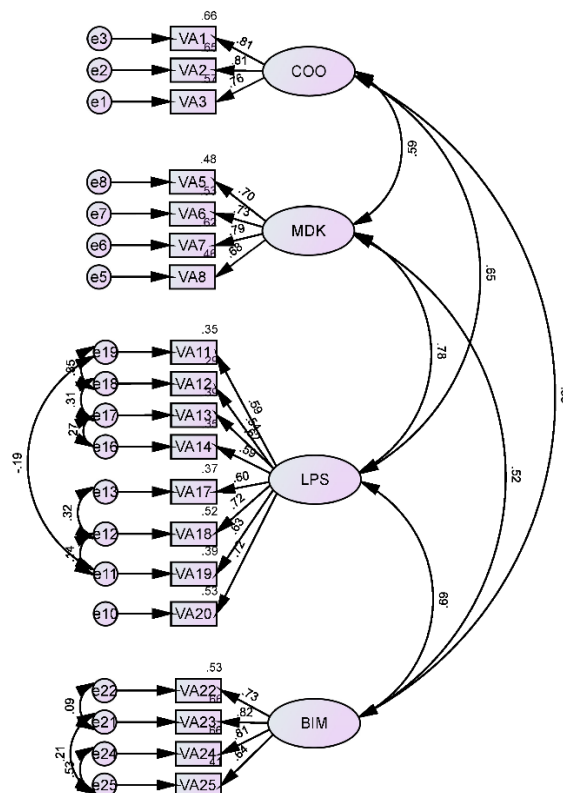


Figure 5-10 – Adjusted measurement model

5.4.2. Model Reliability Analysis

Construct Reliability was evaluated using Cronbach's Alpha and Composite Reliability (CR). The Cronbach's Alpha coefficients for each construct in the study exceeded the recommended threshold of 0.70 (Nunnally & Bernstein, 1994). CR values also ranged from 0.813 to 0.839, surpassing the 0.70 benchmark (Hair et al., 2019). Therefore, CR was established for each construct in the study, as documented in Table 5-7.

The convergent validity of the scale items was assessed using Average Variance Extracted (AVE) (Hair et al., 2019). The AVE values for BIM functionalities and LPS technical measures exceeded the

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threshold value of 0.5 (Hair et al., 2019). However, Collaboration, MD knowledge, LPS Functions, and BIM Functionalities exhibited AVE scores below 0.5. Nonetheless, given that the CR values exceeded the required threshold, it can be inferred that these constructs maintain adequate convergent validity for the present study, as summarised in Table 5-7.

Table 5-7 – Loadings, Reliability, and Convergent Validity

Items	Loadings	Alpha	CR*	AVE**
Collaboration		0.815	0.835	0.628
VA1	0.813			
VA2	0.806			
VA3	0.757			
Making-Do Knowledge		0.811	0.813	0.552
VA5	0.696			
VA6	0.727			
VA7	0.786			
VA8	0.676			
LPS Functions		0.873	0.839	0.397
VA11	0.588			
VA12	0.542			
VA13	0.623			
VA14	0.589			
VA17	0.605			
VA18	0.720			
VA19	0.625			
VA20	0.725			
BIM Functionalities		0.843	0.838	0.567
VA22	0.730			
VA23	0.815			
VA24	0.814			
VA25	0.638			

* CR: Composite Reliability

**AVE: Average Variance Extracted

The discriminant validity of the research was assessed by utilizing both the Fornell and Larcker Criterion approach and the Heterotrait-Monotrait (HTMT) ratio. The Fornell Larcker Criterion allows discriminant

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validity when the square root of a construct's Average Variance Extracted (AVE) surpasses the correlation with other study constructs (Fornell & Larcker, 1981). Nevertheless, the Fornell and Larcker Criterion has been the source of recent criticisms, and scholars have accepted new methods, such as the HTMT Ratio, as alternative techniques. Although the Fornell and Larcker Criteria did not provide evidence of discriminant validity in this study, all HTMT ratios were below the 0.85 threshold value, as (Henseler et al., 2015) recommended. Therefore, the HTMT ratio was used to confirm the discriminant validity. The presented content of Table 5-8 is the results of a closely carried out discriminant validity analysis, where the coefficients and significance values of discrimination are highlighted in Table 5-8.

Table 5-8. HTMT Analysis

	COO	MDK	LPS	AVE
COO				0.628
MDK	0.616			0.552
LPS	0.603	0.765		0.397
BIM	0.332	0.504	0.666	0.567

5.4.3. Structural Model Assessment

The structural equation model is generated through AMOS and was used to test the relationships among dependent variables. Similar to the measurement model criteria, an excellent fitting model is accepted if the value of CMIN/df is below five, which meets the requirements of (Hair et al., 2019), TLI and CFI below 0.90 (Bentler, 1990). Also, an adequate-fitting model was accepted if the AMOS software computed RMR and SRMR between 0.05 and 0.080 (Hair et al., 2019). The fitness measures for the fell within the acceptable range: CMIN/ df = 1.418, TLI=0.932, CFI= 0.946, SRMR= 0.0597, and RMSEA =0.060.

5.4.4. Mediation Analysis

Mediation analysis examines those complex and multi-dimensional draws between two constructs because their influence likely operates not directly but through a third variable called a mediator. In this case, the intermediary variable demonstrates an interfering element in the relationship between the two variables, which explains the underlying mechanisms of the associations. The bootstrapping method investigates mediation within a model with settings of (bootstrap samples = 2000 samples, percentile confidence level (PC) = 90%, Bias-corrected confidence level = 90%). Knowing the basic terms, such as direct and indirect, is vital in mediation analysis.

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Figure 5-11 – Bootstrap settings

The squared multiple correlation was 0.62 for MDK; this shows that the LPS, COO, and BIM account for 62% of the variance in MDK. The square multiple correlation for COO accounts for 0.44; this signifies that LPS functions and BIM account for 44% variance in collaboration. The study assessed the impact of COO, LPS, and BIM on MDK. The effect of LPS on MDK was positive and significant; hence, H2 was supported. However, the impact of BIM on MDK was negative and insignificant. Therefore, H1 was not supported. The effect of the COO on MDK was positive and insignificant, too. Hence, H1 was not supported. The impact of LPS on the COO was positive and significant; hence, H2 was supported.

On the contrary, the BIM impact on the COO was negative and insignificant. Thus, H1 was not supported. Model fit indices and hypothesis results are presented in Table 5-9.

Table 5-9–Moderation analysis for the structural model and model fit indices

Hypothesised Relationship	Standardised Estimates	t-value	p-value	Decision
LPS → MDK	0.698	3.15	<0.001	Significant
BIM → MDK	-0.013	-0.085	0.932	Insignificant
COO → MDK	0.118	1.030	0.303	Insignificant
LPS → COO	0.803	4.309	<0.001	Significant
BIM → COO	-0.257	-1.415	0.157	Insignificant
R-Square				
MDK		62%		
COO		44%		

5. Surveying LPS-BIM strategies for MD mitigation

Model Fitness Indices

CMIN/df = 1.418, TLI = 0.932, CFI= 0.946, SRMR= 0.0597 and RMSEA =0.060.

The study was carried out to investigate the mediation effect of LPS Functions (LPS) and BIM Functionalities (BIM) on the association between COO and MDK, as shown in Figure 5-12. There was insignificant mediation between the Making-Do Knowledge and Collaboration through BIM ($b = 0.033$, $p = 0.314$), rejecting Hypothesis 1. On the contrary, the mediation effect was significant for LPS Functions ($b = 0.268$, $p = 0.02$); evidence favouring Hypothesis 2 was established. Moreover, the direct impact of the COO on MDK with the mediators was insignificant ($b = 0.262$, $p = 0.028$). So, LPS can partially be seen as a channel between Collaboration and MDK. The result of the mediation analysis is shown in Table 5-10.

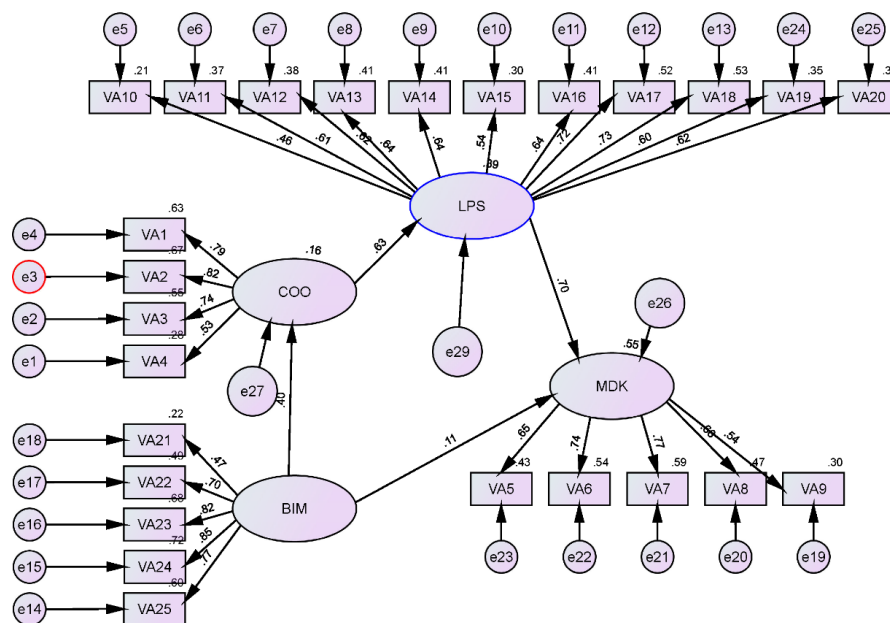


Figure 5-12 – A graphical representation of the applied Mediation Analysis for LPS, BIM, COO, MDK

Table 5-10 – A summary of Mediation Analysis results

Relationship	Direct effect	Indirect effect	Confidence Interval		P-value	Interpretation
			Lower Bound	Upper Bound		
COO → BIM → MDK	0.262	0.033	-0.025	0.192	0.314	No mediation
COO → LPS → MDK		0.268	0.066	0.528	0.002	Partial mediation

5.6. Discussion

Based on Koskela's specification for MD waste, several MD waste elimination strategies will cover this issue related to advancements in production planning and control and Information and Communication Technology (ICT) within the construction industry. It reviews existing research to identify best practices, resulting in four broad classifications of strategies: integration of product and process information, Production Planning and Control, Quality Management and Control, and technology, including local empowerment for humans involved in the project. In particular, the LPS and Total Quality Management are singled out as efficient strategies for producing minimum non-value activities (NVA) waste (Al Hattab & Hamzeh, 2018; Leão et al., 2014). There is an indication of the role played by modern technologies like BIM concerning waste reduction (Etges et al., 2020; Saurin & Sanches, 2014; Tezel et al., 2016). Enhancing the social empowerment approach in the risk assessments and elimination efforts for MD emphasises the requirement for skills training and culture shift in current supervisors and tradespeople working on the project (Alhava et al., 2019). Overall, the consensus emphasises the need for a comprehensive approach integrating theoretical insights with practical methodologies to address MD practices effectively within the construction industry (É. M. Dos Santos et al., 2020a; Emmitt et al., 2012; Fireman et al., 2013b; Formoso et al., 2020; Igwe et al., 2022; Neve & Wandahl, 2018; Pikas et al., 2012; Sukster, 2005). As such, a dynamic BIM-LPS framework for MD management was developed based on the factors identified by the industry respondents.

To avoid the complexity of dynamics systems development (Sterman, 2000). A system structure diagram approach represents an overview of the model, highlighting casual loops and a model's decision structure at a high abstraction level with lower details. This system architecture brings attention to the information that the modeller assumes decision-making uses to govern the flow rate in the system. It also ensures that all components are loosely coupled from each other to ensure independence among components, thereby encouraging their implementation on time. The PSD-driven approach also promotes the separation of data between the algorithm and the technology.

Considering the factors identified from the literature, LPS-BIM strategies for MD mitigation, and a questionnaire survey, a dynamic BIM-LPS framework for MD management was developed, as presented in Figure 5-13. This figure was made to integrate the industrial and technological requirements for a dynamic system incorporating LPS-BIM to mitigate MD practices. This approach also clarifies subsystem boundaries and defines resource flow components in a construction system. The framework development employed is grouped into functional subsystems:

5. Surveying LPS-BIM strategies for MD mitigation

- **Data:** The data collected contains shared knowledge that uses decision-making throughout the construction supply chain.
- **Dynamic Project Management Parameters:** Project management parameters are well-researched and developed into common archetypes (Lyneis et al., 2001).
- **The Last Planner System:** This system includes social and technical parameters to limit the effect of MD by active and collaborative analysis of the potential constraints.
- **BIM Functionalities:** in support of the LPS implementation, this subsystem defines BIM methods and tools for transparent information exchange and analysis.
- **Dynamic output:** this is the final output of the system dynamic models, which includes time series graphs for the variables under study. The dynamic yield also includes presenting the stock values for making-do, constraints, wastes, and other parameters in the system.

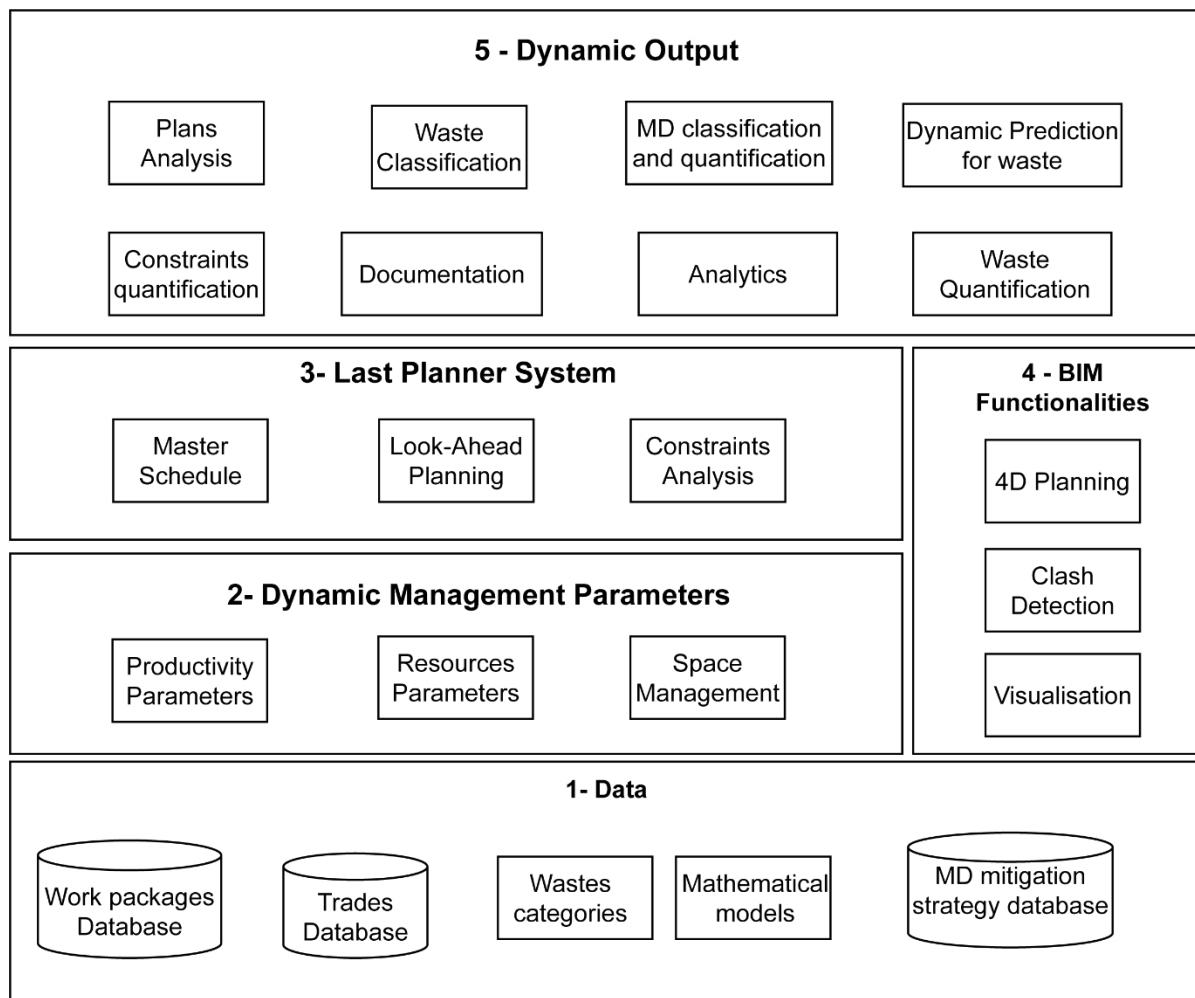


Figure 5-13 – Framework for an LPS and BIM for MD waste mitigation.

5.7. Conclusions

This chapter presents the findings from a questionnaire survey designed to investigate multiple facets of MD within the construction industry. Following a succinct introduction outlining the concept of MD and the overarching research objectives, the survey delves into several key areas. Initially, it aims to assess the current implementation status of lean construction practices, LPS, and BIM within the surveyed population. Subsequently, respondents were asked about their familiarity with the MD concept. Additionally, participants are prompted to identify the primary stakeholders perceived to contribute significantly to MD waste.

Furthermore, the survey includes a component where respondents rank LPS and BIM strategies intended for MD mitigation. The survey responses are then aggregated and categorised into five distinct groups using factor analysis, representing potential strategies for MD mitigation. These categories are delineated as follows: “Integrated Production and Product Information,” “Adaptation Towards LPS and MD free culture,” “Collaborative Commitment towards MD Mitigation,” “Constraints Analysis with Short and Long Terms Planning,” “Active Feedback Mechanisms for MD Incident Resolution.”

6. Mathematical modelling for the LPS-BIM and MD systems

The present chapter offers a detailed process of developing the mathematical model on which the dynamic model is based. The chapter highlights the statistical data collected and analysed and the simulation designs built from data extracted based on the QuizQuality tool. To emphasise the collected and analysed data, the chapter starts with Pareto diagrams. Subsequently, a chi-square test for association was conducted to identify the relationship between the categorical data collected. Multiple Linear Regression Analysis (MLRA) was used to estimate the relationships among MD systems to perform mathematical equations between the different dynamic systems. By MLRA, quantifiable specifications for the system dynamics model were created for planning and control systems, making-do systems, and waste. The dynamic systems are work progress, Making-Do (MD), waste, and constraints systems. The model describes how planning and control systems can be simulated in the System Dynamic Model to determine the consequences on MD, constraints, and waste types.

Further, the control and simulation of conventional planning and controlling showed that MD incidents influenced many tasks. However, the developed SDM in this chapter relied only on technical factors for production planning and control, which lacks the inclusion of social factors, hindering precision in simulating MD decisions' impact. Further investigation is required to model the MD phenomena from a socio-technical perspective holistically.

6. Mathematical modelling for the LPS-BIM and MD systems

6.1. Introduction

Building upon the Casual Loop Diagram (CLD) in Chapter 4, Figure 6-1 illustrates a generic view of the components of the proposed System Dynamics Model. The developed SDM consists of four vital subsystems: 1) Work progress, which represents work in progress (WIP), constraints, and finished works 2) the Making-Do (MD) Subsystem, including MD and Waste stocks; 3) resources variables, including space stock, labours stock, and productivity dynamic variable, 4) LPS-BIM subsystem consists of LPS social, technical factors and factors that represent BIM functionality. The relationships among the first three subsystems examine technical factors in the construction planning and control process; by employing statistical analysis in studied projects, it became possible to provide a regression model derived from the data collected. The fourth subsystem, LPS-BIM, is evaluated through structural equation modelling to estimate the effect of LPS functions, Collaboration, making Do knowledge, and BIM functionalities on MD and the overall production system. Table 6-1 outlines the categories of constraints (P1 to P6), MD categories (CAT1 to CAT2), and impacts (I1 to I5).

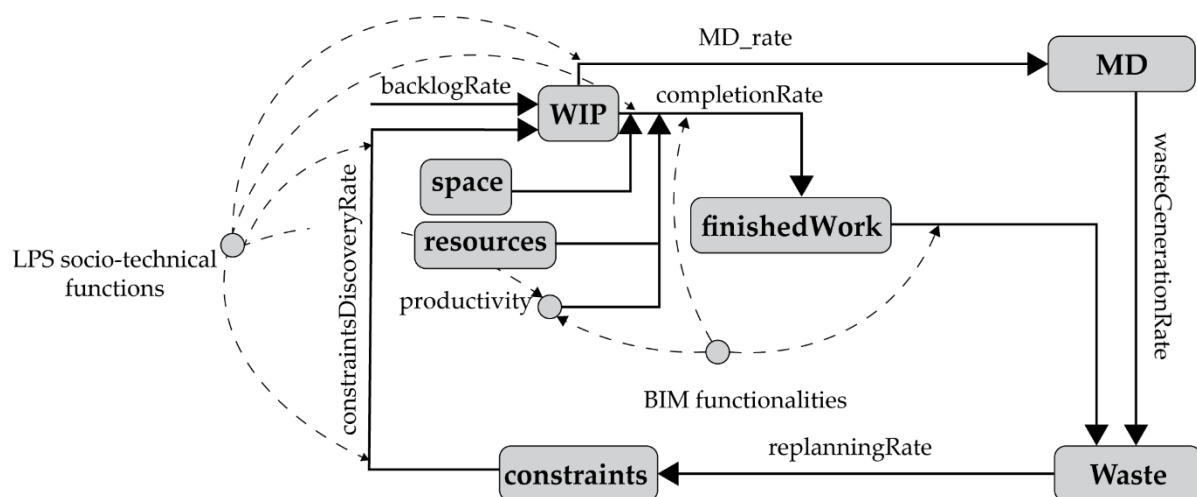


Figure 6-1 – Generic view of the dynamic systems for MD mitigation

Table 6-1– Constraints, MD, and MD impacts

Constraints		MD Categories		MD impacts	
P1	External Conditions	CAT1	Access and Movement	I1	Decreased Productivity
P2	Information	CAT2	Component Adjustment	I2	Material Waste
P3	Interdependent Tasks	CAT3	Equipment/Tools	I3	Quality Deviation
P4	Labor	CAT4	Sequencing	I4	Rework
P5	Materials and components	CAT5	Workspace	I5	Unfinished works

The mathematical models presented in this chapter reveal some of construction management's dynamic and complex relationships, especially when addressing MD and its impacts. This chapter underlines the dynamic interplay between technical factors that influence decisions regarding MD practices. Proposed interventions, including enhanced constraints analysis and MD identification mechanisms, aim to optimise planning and control processes to reduce the number of making-do tasks. Following the lean paradigm, this study suggests preventive strategies. Despite minor variances observed between simulated and actual values of the system dynamic model discussed within, this chapter recommends broadening constraint removal and exploring interdependencies among MD categories and impacts. This finding calls for actions to advocate for a comprehensive and holistic MD management approach using LPS-BIM in construction projects.

The chapter is organised as follows: first, it outlines the methodology employed for data collection. Subsequently, a comprehensive analysis is conducted to assess internal validity. Second, chi-square tests for the association are utilised for this purpose, alongside multiple regression analysis to explore the interrelationships depicted in Figure 6 1. The subsequent section delineates traditional planning systems' developed Stock-Flow-Diagram (SFD). Fourth, a simulation spanning 52 months is conducted to observe the accumulation of "Making-Do" and its consequential impacts and underlying causes. Finally, the chapter concludes by summarising key findings and advocating for actionable steps, setting the stage for subsequent chapters.

6.2. Methodology

6.2.1. Data Collection

The informing case studies are used in this chapter as a method of research that includes a detailed examination of Making-Do waste as a single instance to conclude broader insights and theories while understanding complex phenomena from different projects (F. Chen et al., 2020; Dixon-Woods et al., 2007; Ickis & Omazić, 2013). The data was collected from three cases: A, B, and C. Case A is a Brazilian project constructed by company M between March 2016 and March 2021; it involved 20-story towers with 480 units total on 9,445 square meters of land used. Case B is another Brazilian project constructed by company (N) between March 2020 and September 2023; it involved the construction of two 15-story towers with 45 units each, using 2,860 square meters of land use. Case C took place in France by company (K) between February 2019 and March 2021, with the primary objective being the renovation of a single seven-story building with 140 units on 1,223 square meters. Case A shows

6. Mathematical modelling for the LPS-BIM and MD systems

large-scale, high-density construction; Case B indicates a potentially phased or specialised approach, given the longer timeline; and Case C demonstrates a rehabilitation project in a different country.

Table 6-2– Comparative Overview of Multistorey Condominium Projects: Case A, Case B, and Case C

Case	Case A	Case B	Case C
Photos			
Enterprise Code	M	N	K
Country	Brazil	Brazil	France
Start and Finish Dates	03/2016-03/2021	03/2020-09/2023	02/2019-03/2021
Project type	Construction multistorey condominium	Construction multistorey condominium	Rehabilitation multistorey building
Description	Three towers	Two towers	One tower
Floors /tower	20	15	7
No of units	480	45	140
Land use (m²)	9,445	2,860	1,223

Data used in this study (as elaborated in Figure 6-2) originates from the QuizQuality tool implemented in the cases under investigation. This tool actively contributed to large-scale construction projects by monitoring work quality and generating checklists for quality inspections. Additionally, it generated reports detailing the causes of suboptimal production. Subsequently, management and engineers received these findings, empowering them to make informed decisions and address issues, ultimately improving production outcomes. Table 6-2 summarises and compares case studies of the collected data that showcase three multistorey condominium projects.

Six thousand four hundred twenty-one making-do incidents were collected and presented for the primary care of project managers. The relationships between project phases, task prerequisites, incident categories, and negative impacts on production systems were analysed.

6. Mathematical modelling for the LPS-BIM and MD systems

	CompanyName	Obra	WorkName	Unidad	LocalDe	SublocalDescr	TipoDe	TipoDocumentoDescricao	Docum	DocumentoDescricao	CaracteristicaDescricao
1	Construtora Colmeia S.A.	550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Quantidade de peças por posição
1		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Bitolas dos Ferros
1		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Posicionamento (estribos)
1		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Traspasse/ Ancoragem
2		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Alinhamento de Vigas
2		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Nivelamento de Vigas e Lajes
2		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Prumo de Vigas e Pilares
2		550	Gol Village	Bloco 70	Coberta	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Esquadro pilares e lajes
3		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Alinhamento de Vigas
3		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Nivelamento de Vigas e Lajes
3		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Prumo de Vigas e Pilares
3		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Esquadro pilares e lajes
4		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Alinhamento de Vigas
4		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Nivelamento de Vigas e Lajes
4		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Prumo de Vigas e Pilares
4		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Esquadro pilares e lajes
5		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Quantidade de peças por posição
5		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Bitolas dos Ferros
5		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Posicionamento (estribos)
5		550	Gol Village	Bloco 73	02º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-05	ARMAÇÃO	Traspasse/ Ancoragem
6		550	Gol Village	Bloco 74	01º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Alinhamento de Vigas
6		550	Gol Village	Bloco 74	01º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Nivelamento de Vigas e Lajes
6		550	Gol Village	Bloco 74	01º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Prumo de Vigas e Pilares
6		550	Gol Village	Bloco 74	01º Pav. -	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-04	FORMA E DESFORMA	Esquadro pilares e lajes
7		550	Gol Village	Bloco 75	Fundação	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-03-0	FUNDAÇÃO DIRETA/INDIRETA	Posicionamento da Forma
7		550	Gol Village	Bloco 75	Fundação	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-03-0	FUNDAÇÃO DIRETA/INDIRETA	(Dimensões da Forma
7		550	Gol Village	Bloco 75	Fundação	Indefinido	IT	INSTRUÇÃO DE TRABALHO	7.5.1-03-0	FUNDAÇÃO DIRETA/INDIRETA	Quantidade

State	Enterprise Code	Project Code	Projects	Trades	Stage	Sub-stage	Activity	Prerequisite	Category	Impact
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Mason	Structure	Superstructure	Concreting of the suprastructure	Information	Component Adjustment	Unfinished Works
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Carpenter	Structure	Superstructure	Execution of the forms of the suprastructure	Labor	Sequencing	Rework
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Mason	Structure	Superstructure	Concreting of the suprastructure	Information	Component Adjustment	Unfinished Works
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Plumber	Fixtures and fittings	Appliances and metals	Metals	Labor	Component Adjustment	Rework
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Electrician	Fixtures and fittings	Electrical installations	Wires and cables	Materials and components	Sequencing	Unfinished Works
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Tile Setter	Cladding and Finishes	Pavement works	Skirting boards/sills	Materials and components	Component Adjustment	Rework
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Tile Setter	Cladding and Finishes	Pavement works	Floor covering	Materials and components	Component Adjustment	Rework
CEARÁ	M	M	AQUARELA CONDOMÍNIO CLUBE	Carpenter	Cladding and Finishes	Carpentry and locksmithing	Metal door/Gate	Labor	Component Adjustment	Rework

Figure 6-2 – Example of raw data collected and classified into Phases, Substages, Prerequisites, MD categories, and MD impacts. This figure is not mentioned in the text.

The work packages in the three projects (A, B, and C) followed the same work breakdown structure (WBS), which included five stages: S1: Cladding and finishes, S2: Work Completion, S3: Walls and Panels, S5: Fixtures and fitting. Additionally, these phases (stages) were broken down into substages (SS1- SS11) as illustrated in Figure 6-3; however, the substages “Complementary facilities” and “Ceiling and decorative elements” were excluded due to the lack of collected data within these substages.

6. Mathematical modelling for the LPS-BIM and MD systems

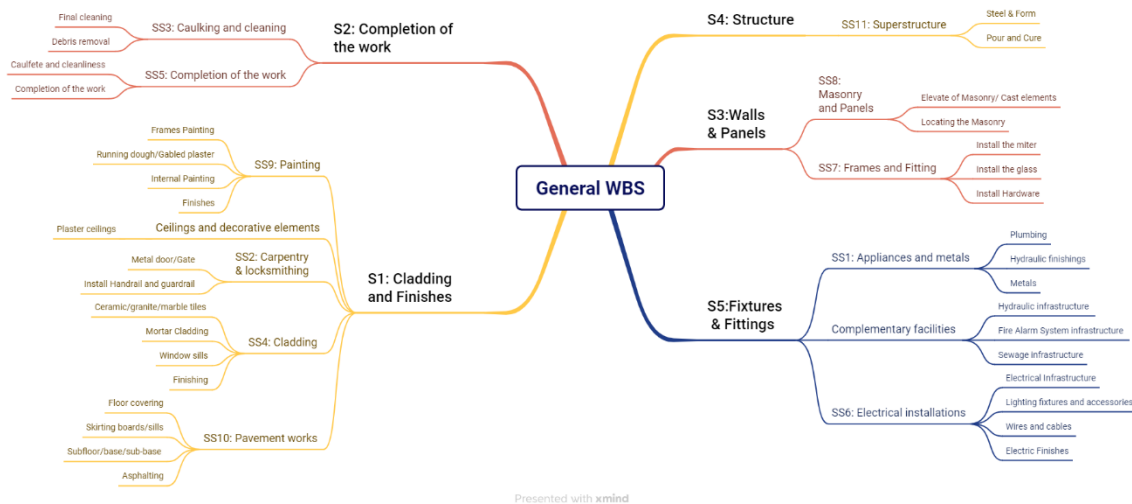


Figure 6-3 – General Work Breakdown Structure used for the three projects

6.2.2. Data Analysis

This section examines the initial data analysis of primary components using a set of statistical instruments to ensure internal consistency and achieve a mathematical model to be used in the dynamic model in Sections 6.5 and 6.6. The main objective of this analysis is to determine factors associated with the disclosure of Making-Do status to construction production systems.

Pareto charts are deployed in the exploratory data analysis phase for the three projects in Table 6-2 to delve into the distribution of dummy variables. (Figure 6-4, Figure 6-5, Figure 6-6, Figure 6-7, and Figure 6-7) present a comprehensive analysis of studied projects using Pareto charts. This quality tool prioritises and displays the most significant factors in a dataset. This approach provides insights into the patterns encapsulated by these variables. The presented figures depict a Pareto chart analysing the frequency of infected phases and sub-stages. Concerning phases, Figure 6-4 50% of MD incidents are associated with cladding and finishes, 12.1% with work finishes, and 9.2% with fixtures and fittings. Furthermore, stages, such as walls and panels, fixtures, and fittings, contribute 9.2%, 8.5%, and 7.2%, respectively.

6. Mathematical modelling for the LPS-BIM and MD systems

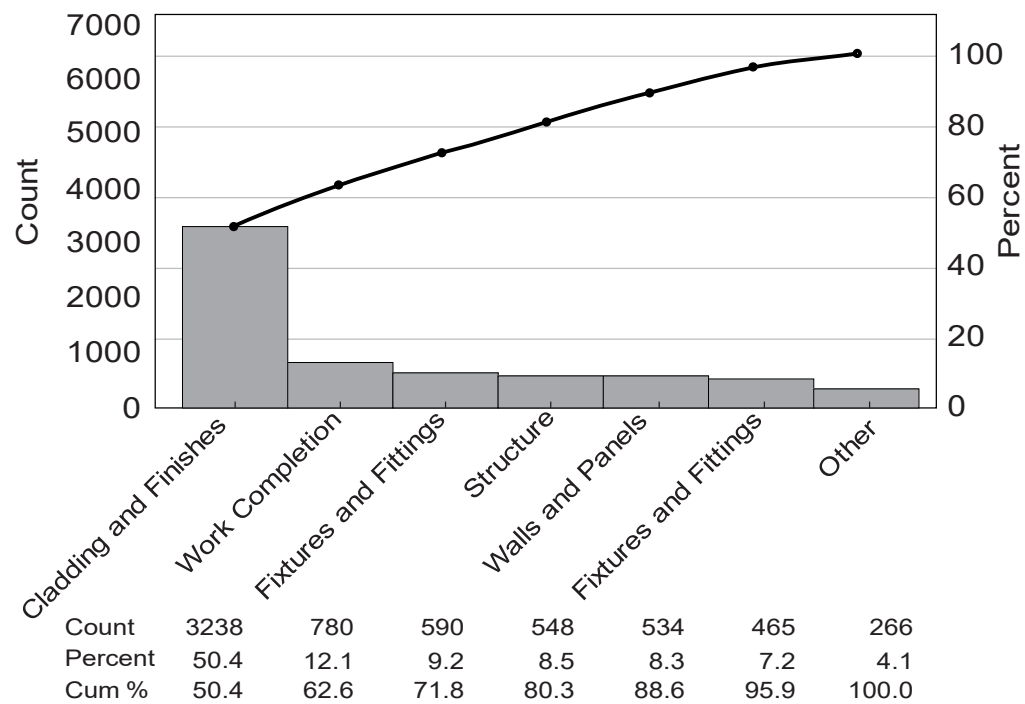


Figure 6-4– An examination of the distribution pattern within the phases primarily impacted by MD incidents in the analysed cases (according to data collected).

The Pareto chart Figure 6-5 breaks down the frequency of infected sub-stages to complement the previously mentioned project phases. According to the chart, pavement works, painting, carpentry, and locksmithing are linked to 16.5%, 14.2%, 13.2% and 11.7% of MD incidents, respectively. Additionally, frames and fittings account for 9.2% of incidents, while complementary facilities, appliances, and metals contribute 8.8% to the total cases. Electrical installations, cladding, masonry, and panels represent 5.0%, 4.0%, 3.5%, and 2.6% of incidents, respectively.

6. Mathematical modelling for the LPS-BIM and MD systems

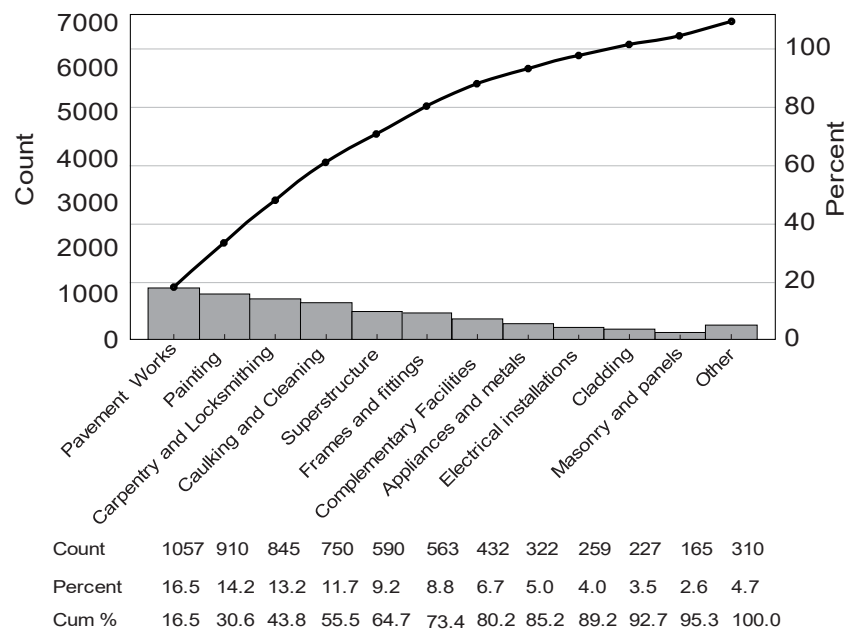


Figure 6-5– An analysis of the distribution among the sub-stages most affected by MD incidents in the examined cases (according to data collected).

In line with the theoretical framework discussed in Chapter 4, grounded in the seven flows identified by Koskela in 1992, this study performs another Pareto chart to outline the frequency of lacking prerequisites (constraints analysis) that lead to MD incidents. Figure 6-6 discloses that deficiencies in the Labor flow account for 50.1% of MD incidents, followed by 33.3% associated with inadequacies in materials and components. Moreover, interdependencies with other tasks account for 6.9% of incidents, while 5.0% are attributable to issues related to physical locations, specifically space constraints. Additionally, challenges arising from external conditions, information gaps, and equipment or tools inadequacies constitute a small proportion of 4.6%.

6. Mathematical modelling for the LPS-BIM and MD systems

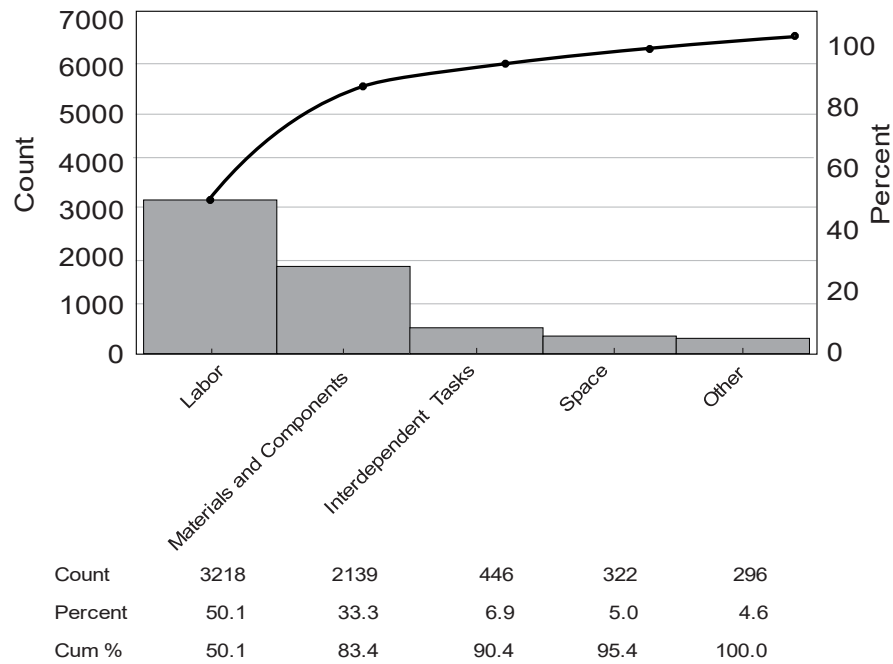


Figure 6-6 – Analysing the task prerequisites (not resolved constraints) caused MD incidents: a study of affected tasks distribution in examined cases (according to data collected)

Notable patterns are revealed in the distribution of the MD categories, as shown in Figure 6-7. Component adjustment emerges as the most affected category, encompassing a significant majority at 67.4%. This stat indicates a substantial need for alterations and modifications in components within the project context. Sequencing follows, accounting for 17.8%, indicating challenges related to the order and arrangement of project tasks. Access and movement issues contribute to 10.8%, highlighting hindrances in the accessibility and mobility aspects of the project environment. A more minor but noteworthy 4% is attributed to challenges associated with equipment and tools, storage, workspace, and protection, underscoring the diverse issues impacting these areas.

6. Mathematical modelling for the LPS-BIM and MD systems

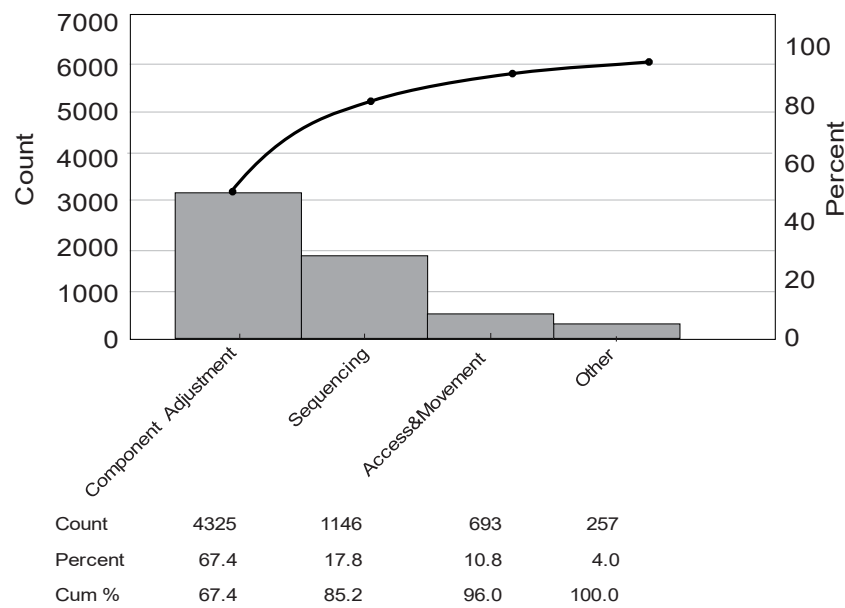


Figure 6-7 – Analysing Categories of MD: a study of affected task distribution in examined cases (according to data collected).

Regarding MD impacts in Figure 6-8, the impact of rework constitutes the largest proportion at 56.1%, showing the significant need for revisiting and redoing tasks to rectify errors and discrepancies. Unfinished works account for 21.6% of the challenges, highlighting the persistence of incomplete functions within the project context. The quality deviation is 9.2%, where the final output does not meet the specified quality standards. Declined productivity at 8.5% indicates a reduction in the efficiency and output levels, posing additional challenges to project progress. Material waste, contributing to 4.7%, reflects inefficiencies in the utilisation of resources, while demotivation shares this percentage, suggesting the presence of a disengaged or demoralised workforce within the project setting.

6. Mathematical modelling for the LPS-BIM and MD systems

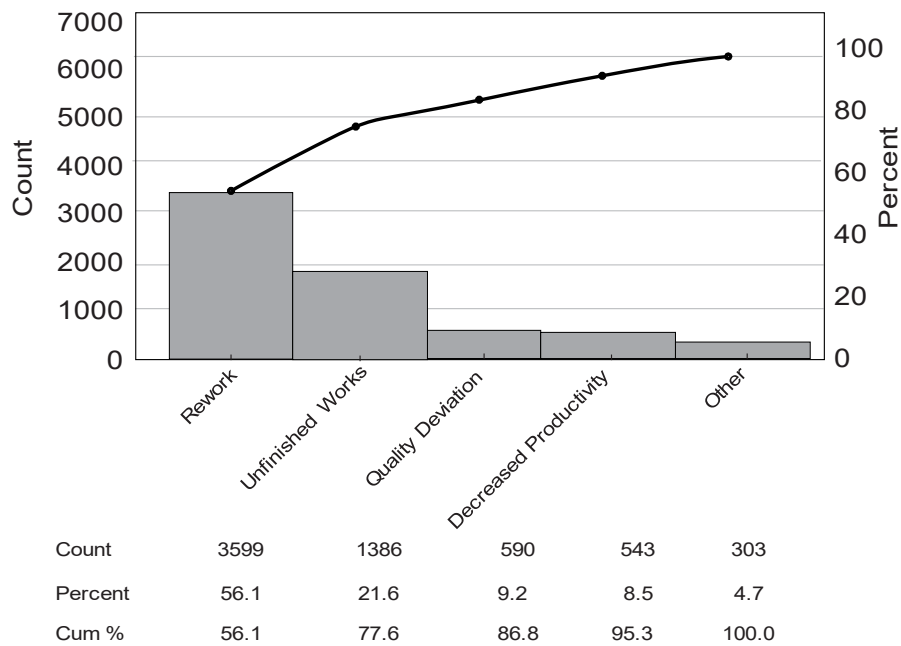


Figure 6-8 – Analysing the Impact of MD Incidents on Production Systems: A Study of Affected Distribution in Examined Cases

6.3. Tests for association

Test for association advances data interpretation techniques to verify the categorical dataset's overall coherence and comprehensiveness. In this exploratory technique for data analysis, Chi-Square tests aim to measure the internal consistency among different variable groups (Hastie et al., 2009). This test also evaluates correlations and dependencies among variables. This approach ensures a comprehensive understanding of the data, facilitating robust insights and aiding strategic decision-making. The chi-square test aims to determine if there is a significant association between prerequisites and MD categories and MD impacts (waste) and MD categories.

Null Hypotheses:

H0-1: There is no significant association between prerequisites (constraints) and the MD categories.

H0-2: Waste generated is not significantly associated with the MD categories.

Alternative Hypotheses:

H1-1: There is a significant association between prerequisites (constraints) and the MD categories.

H1-2: Waste generated is significantly associated with the MD categories.

The chi-square test in Table 6-3 assesses the dependencies between task constraints and the MD categories. Observed frequencies from Table 6-3 are compared to expected frequencies by assuming a dependency between variables. The outcomes reveal a significant association between task prerequisites and MD categories. For instance, labour-related constraints show a notable association with sequencing and component adjustment, indicating that these factors might contribute significantly to MD generation. Conversely, external conditions and workspace have minimal associations with MD categories. Such evidence informs that it is possible to provide interventions to mitigate MD by addressing specific task constraints that are strongly associated.

Table 6-3 – Association tabulation test for Task prerequisites (Left Column) and MD categories (Top Row) 6241

	CAT1: Access/ Movement	CAT2: Component Adjustment	CAT3: Equipment/ Tools	CAT4: Sequencing	CAT5: Workspace	Total
P1: External conditions	0	132	0	0	0	132
P2: Information	0	42	1	65	0	108
P3: Interdependent tasks	39	158	0	249	0	446
P4: Labour	420	2182	6	608	1	3217
P5: Material and components	50	1805	57	224	0	2136
P6: Space	197	0	0	0	96	293
Total	706	4319	64	1146	97	<u>6332</u>

As in Table 6-4, the Pearson Chi-Square statistic is 4049.103 with 20 degrees of freedom (DF) (equation 3.6), showing that the two datasets (observed and expected frequencies) have a significant relationship. Furthermore, the Likelihood Ratio Chi-Square statistic was 2456.924, with 20 DF. These statistics are higher than the critical value (37.57 obtained from distribution tables), showing that the null hypothesis is rejected and there is a strong association between the variables listed in Table 6-4, which is significant and requires further exploration to understand the nature of this association and its impacts.

6. Mathematical modelling for the LPS-BIM and MD systems

Table 6-4 - Chi-Square test for prerequisites and MD categories

	Chi-Square	DF	P-Value
Pearson	4049.103	20	0.001
Likelihood Ratio	2456.924	20	0.001

Table 6-5 illustrates the association between MD categories and different types of MD impacts. The chi-square analysis provides insights into how specific types of waste (MD impact) relate to MD practices within construction projects. Significant associations can be observed in Table 6-5, calculated for a specific combination of project phase and task prerequisite, represented in each cell of the Table, revealing the degree of dependence between these variables. The analysis shows significant interactions across project phases, particularly in Materials and components, Labor, Equipment, and Tools tasks. The high chi-square values emphasise the significance of comprehending the intricate interplay between project phases and task prerequisites.

Table 6-5 – Association tabulation test for MD Categories (Left Column) and construction (impacts) waste (Top Row)

	I1: Decreased productivity	I2: Material waste	I3: Quality Deviation	I4: Rework	I5: Unfinished Works	Total
CAT1: Access/Movement	345	1	210	134	16	706
CAT2: Component Adjustment	21	262	253	2940	843	4319
CAT3: Equipment/Tools	58	2	0	3	1	64
CAT4: Sequencing	18	15	106	488	519	1146
CAT5: Workspace	85	0	12	0	0	97
Total	527	280	581	3565	1379	6332

The values in Table 6-5 represent the frequency of each MD Category-Impact pair. For example, there were 706 instances where the 'Access/Movement' impact was associated with 'Decreased Productivity,' and 4319 cases where the 'Access/Movement' impact was associated with 'Component Adjustment' impact. This tabulation provides a detailed insight into the relationships between different MD

6. Mathematical modelling for the LPS-BIM and MD systems

Categories and their impacts, helping to understand the prevalence and patterns of these incidents in the given context.

Table 6-6 presents a Chi-Square analysis that used Pearson and Likelihood Ratio tests to explore the relationship between MD categories and waste (MD impact) variables in Table 6-5. The Pearson Chi-Square statistic yielded a value of 4361.046 with 16 degrees of freedom, resulting in a p-value of 0.001, signifying a significant association between the variables under investigation. Similarly, the Likelihood Ratio Chi-Square test produced a statistic of 3150.791 with 16 degrees of freedom and a p-value of 0.001, reaffirming the observed relationship's vital statistical significance. These statistics are higher than the critical value (40.99 obtained from distribution tables), showing that the null hypothesis is rejected and there is a strong association between the variables listed in Table 6-5.

Table 6-6 – Chi-Square test for MD categories and MD impacts

	Chi-Square	DF	P-Value
Pearson	4361.046	16	0.001
Likelihood Ratio	3150.791	16	0.001

6.4. Multiple Regression Analysis

Multiple Linear Regression Analysis (MLRA) is used to quantify the level of association between the dependent variables, allow control over confounding variables, refine the gained understanding from association tests by controlling other variables, allow for the development of predictive models for forecasting the behaviour of dynamic systems, and to validate the hypothesis providing the reliable basis of conclusions drawn from the test for associations (Hair et al., 2019). The fundamentals of linear regression analysis were shortly introduced in Chapter 3 (Subsection 3.3.4), and regression analysis and modelling techniques were introduced to comprehend the development of a mathematical model encompassing the technical factors contributing to MD. Regression analysis incorporates predictors such as project phases, teams, and task prerequisites, while the dependent variables encompass MD categories and the impact of MD on generating other production wastes. This analysis aimed to derive a regression equation, which will serve as input for the subsequent development of the SDM in the following chapter. Continuous predictors underwent standardisation by dividing the values by the standard deviation. Graphical outputs include histograms of residuals, standard probability plots of residuals, residuals versus fits, and residuals versus order, alongside Pareto charts for standardised residuals, which are shown in the example in Figure 6-9.

6. Mathematical modelling for the LPS-BIM and MD systems

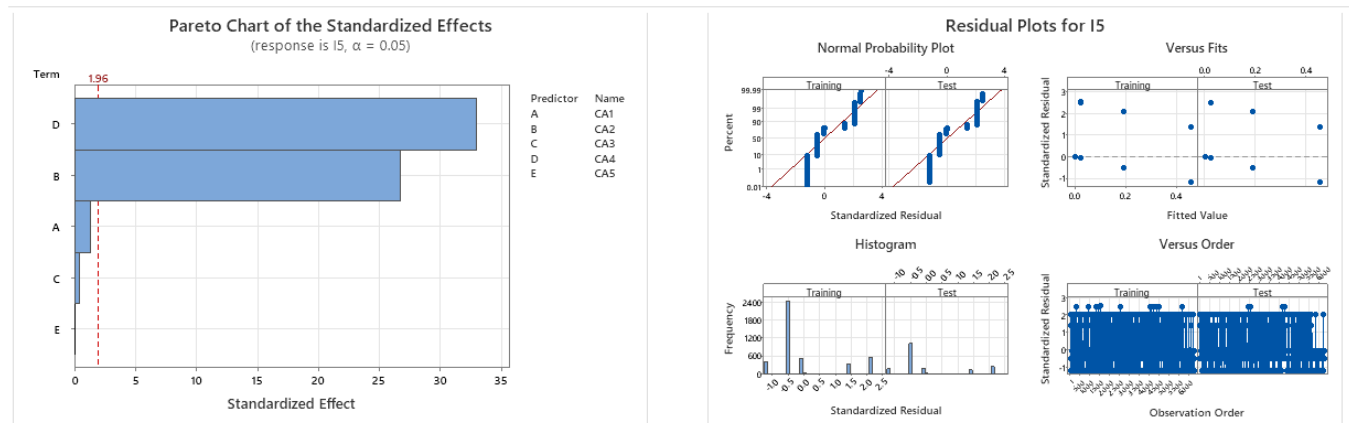


Figure 6-9 – Graphical outputs of a single MLRA

Furthermore, Durbin-Watson statistics had also been employed using all observations. Table 6-7 provides a summary of multiple regression models whereby three validation statistics are applicable, and these include standard deviation (S), R-squared, and Durbin-Watson statistics. The standard deviation (S) defines how well the model estimates the response using the distance between data values and the fitted values. The coefficient of determination calculated by the formula R-squared represents the proportion of the variance in the dependent variable that the independent variables can explain. At the same time, the Durbin-Watson statistic tests whether there is autocorrelation in the residuals or not.

Table 6-7 presents a summary of multiple regression models (P1-P6, CAT1-CAT5, and I1-I5), highlighting key validation statistics. Specifically, they include the Standard Deviation (S), the coefficient of multiple determination R-squared (R^2), and the Durbin-Watson statistic. The lower the Standard Deviation (S), the higher the ability to predict the dependent variable. Thus, P2 has the lowest S = 0.743, meaning that it has the best prediction, while P4 has the highest S = 6.269, meaning that it has the least prediction. The coefficient of determination or R-squared (R^2) indicates the percentage of variances in the data that is attributable to the model; the models with the highest R^2 are CAT2 with 99.93%, followed by P2 with 76.33%, which indicates that the former has higher explanatory ability than the latter. Autocorrelation in the residuals is checked by the Durbin-Watson statistic, where most of the models have values near about 2, which is good since it shows very minimal autocorrelation. Nevertheless, P3 and CAT2 have values more than 2, which may imply negative auto-correlation, while CAT1 and CAT5 have values less than 2, implying positive auto-correlation. These statistics collectively provide insights into the models' performance, predictive accuracy, and the independence of residuals, contributing to the robustness of the regression analysis.

Table 6-7 – Summary of the Multiple Regression Models (P1-P6, CAT1-CAT5, and I1-I5)

6. Mathematical modelling for the LPS-BIM and MD systems

	Standard Deviation (S)	R-sq	Durbin-Watson Statistic
P1: External conditions	0.914	91.22%	1.568
P2: Information	0.743	76.33%	2.269
P3: Interdependent tasks	2.175	91.03%	2.364
P4: Labour	6.269	97.70%	1.930
P5: Material and components	4.043	98.68%	1.502
P6: Space	1.821	90.90%	2.011
CAT1: Access/Movement	0.935	98.22%	1.190
CAT2: Component Adjustment	1.667	99.93%	1.464
CAT3: Equipment/ Tools	0.571	78.52%	1.343
CAT4: Sequencing	1.978	99.17%	1.755
CAT5: Workspace	0.664	94.85%	1.145
I1: Decreased productivity	1.684	82.78%	1.954
I2: Material waste	0.830	94.26%	1.755
I3: Quality Deviation	1.873	96.31%	1.916
I4: Rework	5.230	99.09%	1.521
I5: Unfinished Works	3.185	98.11%	2.140

6.4.1. Regression Analysis for Construction Constraints

Table 6-8 details the outlines of the regression equations, applying coefficients of the independent variables project substages (SS1-SS11)¹ to examine the relationship with project constraints or prerequisites in each type. The p-values of all factors are less than 0.05, indicating the presence of at least one relationship among dependent and independent variables.

Table 6-8 – Regression tabulation for task prerequisites (P1-P6) in relation to sub-stages (SS1-SS11)

Dependent variable	Term expressed by Sub-Stages
P1	1.78 SS1 - 1.15 SS2 + 1.147 SS3 + 0.898 SS4 + 0.830 SS5 - 1.39 SS6 + 1.459 SS7 + 2.161 SS8 - 0.944 SS9 - 0.324 SS10 - 0.274 SS11
P2	1.209 SS1 - 0.057 SS2 + 0.261 SS3 - 0.101 SS4 + 0.194 SS5 - 0.835 SS6 + 0.913 SS7 - 0.056 SS8 - 0.389 SS9 + 1.027 SS10 + 0.256 SS11
P3	6.65 SS1 - 4.00 SS2 + 1.618 SS3 + 1.10 SS4 + 2.555 SS5 - 3.55 SS6 + 5.69 SS7 + 3.52 SS8 - 2.77 SS9 + 2.10 SS10 - 0.096 SS11
P4	34.6 SS1 - 23.3 SS2 + 12.86 SS3 + 9.57 SS4 + 15.91 SS5 - 18.8 SS6 + 28.1 SS7 + 27.3 SS8 - 13.22 SS9 + 3.6 SS10 - 1.98 SS11
P5	29.1 SS1 - 15.0 SS2 + 13.83 SS3 + 8.20 SS4 + 11.97 SS5 - 15.6 SS6 + 24.2 SS7 + 18.28 SS8 - 12.29 SS9 + 6.62 SS10 - 1.32 SS11
P6	4.03 SS1 - 3.98 SS2 + 2.045 SS3 + 1.29 SS4 + 1.603 SS5 - 2.64 SS6 + 2.69 SS7 + 4.40 SS8 - 1.45 SS9 + 0.58 SS10 - 0.576 SS11

¹ SS1- SS11 are outlined in the WBS according to Figure 6-3

6. Mathematical modelling for the LPS-BIM and MD systems

6.4.2. Regression analysis for MD categories

Table 6-9 delineates the mathematical relationship between constraints and the dependent variable MD categories. The p-values of all factors are less than 0.05, indicating the presence of at least one relationship among dependent and independent variables. These regression results underscore the significant influence of various constraints on MD practices. Interdependent tasks, labour, materials, external conditions, and space emerge as crucial determinants of MD extent in construction projects. Effective management of these constraints is imperative for minimising delays and ensuring a continuous flow. Similar conclusions have been drawn in other literature, such as the theory proposed by Koskela (2004), the exploratory study of Formoso et al. (2011), and the empirical studies conducted by Leao et al. (2014) and Amaral et al. (2022).

Table 6-9 – Regression tabulation for MD categories (CAT1-CAT5) concerning constraints (P1-P6).

Term	Term expressed by constraints
CAT1	$0.02037 P3 + 0.07017 P4 + 0.01229 P5 + 0.14895 P6$
CAT2	$0.14288 P1 + 0.05007 P2 + 0.09046 P3 + 0.33544 P4 + 0.40196 P5$
CAT3	$0.02037 P3 + 0.07017 P4 + 0.01229 P5 + 0.14895 P6$
CAT4	$0.14288 P1 + 0.05007 P2 + 0.09046 P3 + 0.33544 P4 + 0.40196 P5$
CAT5	$0.07942 P2 + 0.14506 P3 + 0.09304 P4 + 0.04725 P5$

6.4.3. Regression Analysis for MD Impacts

Table 6-10 explores the relationship between MD categories and construction waste (specifically, I1: decreased productivity, I2: Material waste, I3: Quality Deviation, I4: Rework, I5: Quality Deviation). The p-values of all factors are less than 0.05, indicating the presence of at least one relationship among dependant (MD categories) and independent variables (MD impact or waste). These regression findings underscore the significant influence of various MD categories on construction waste generation. MD categories emerge as crucial determinants of construction waste. Effective mitigation of these MD practices is essential for eliminating construction waste at its source and enhancing the value delivered to internal and external customers.

Table 6-10 – Regression tabulation for MD impact (I1-I5) concerning MD categories (CAT1-CAT5)

Term	Term expressed by MD categories
I1	$0.16256 CAT1 + 0.00200 CAT2 + 0.08783 CAT3 + 0.00628 CAT4 + 0.10309 CAT5$
I2	$0.00061 CAT1 + 0.02621 CAT2 + 0.00244 CAT3 + 0.00580 CAT4$

6. Mathematical modelling for the LPS-BIM and MD systems

I3	$0.08889 \text{ CAT1} + 0.02914 \text{ CAT2} + 0.03140 \text{ CAT4} + 0.01974 \text{ CAT5}$
I4	$0.05540 \text{ CAT1} + 0.31987 \text{ CAT2} + 0.00732 \text{ CAT3} + 0.16571 \text{ CAT4}$
I5	$0.00731 \text{ CAT1} + 0.08848 \text{ CAT2} + 0.00244 \text{ CAT3} + 0.17585 \text{ CAT4}$

6.5. System Dynamic Simulation for Technical Factors of Making-Do Waste

The ensuing schematic illustrates the Stock and Flow Diagram (SFD) encapsulating the structural dynamics characterising the traditional planning and control system in production, influenced by the Making-Do waste. This system comprises four distinct subsystems: (1) the planning and control subsystem, (2) the constraints analysis subsystem, (3) the Making-Do subsystem, and (4) the Making-Do impacts subsystem. The SFD employs conventional planning configurations for simulation purposes, eschewing utilising the LPS and BIM. The diagram delineates a spectrum of dynamic variables interacting with the stocks and flows.

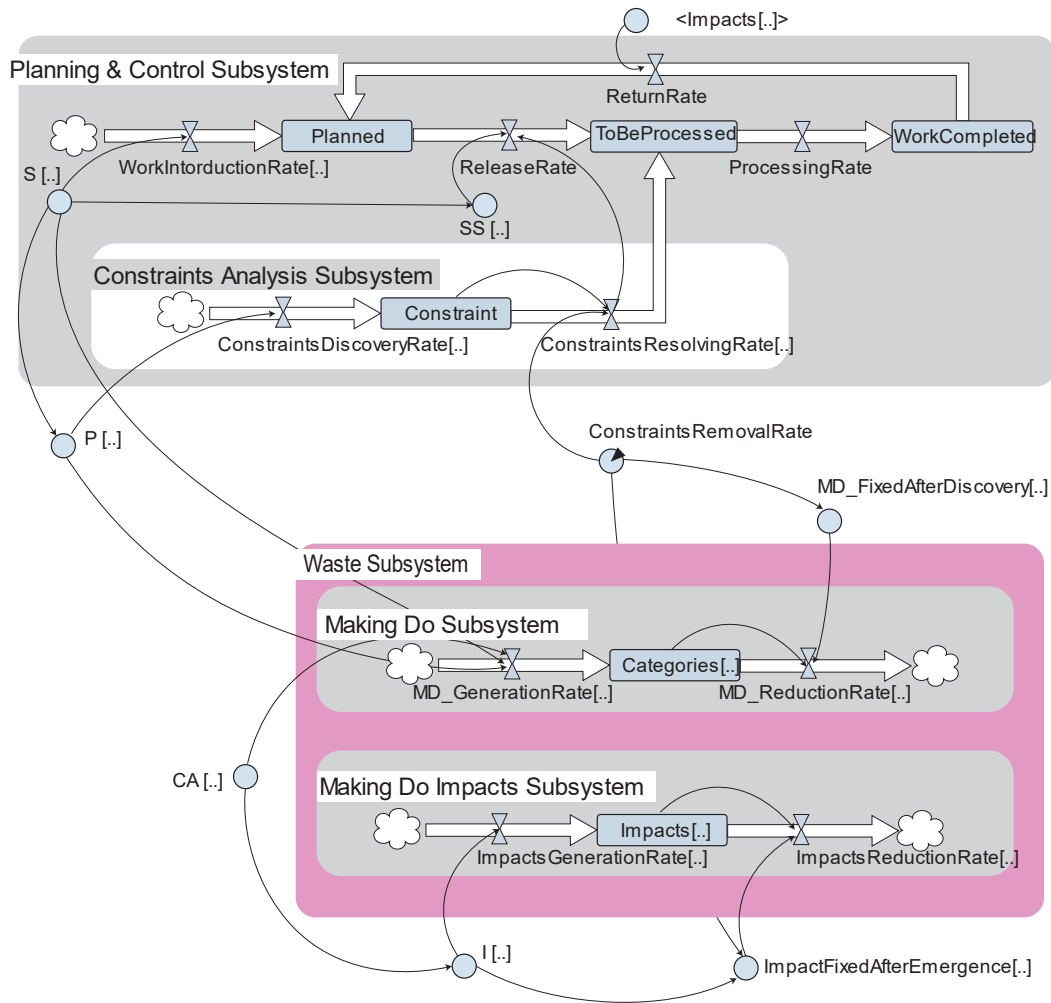


Figure 6-10– Stock and Flow Diagram for Traditional Production Planning and Control

6.5.1. Planning and Control Subsystem

The planning system is contingent upon a dynamic interplay among three pivotal stocks, specifically the Planned, ToBeProcessed, and WorkCompleted, reflecting the cumulative progression from planning tasks to their ultimate completion as dictated by the Planned stock. These stocks delineate their impact through three fundamental flows: WorkIntroductionRate, ReleaseRate, and ProcessingRate, in conjunction with the ReturnRate.

The WorkIntroductionRate denotes the rate of change associated with introducing new tasks into the plan, contingent upon a function of tasks within the phase (S). Simultaneously, the release rate is predicated on the removal of constraints by the project team, signifying the selection of non-constrained tasks for processing. The resolution of constraints within the Constraints Analysis Subsystem, as determined by ConstraintsResolvingRate, influences the ReleaseRate.

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Consequently, the ProcessingRate governs the transformation of tasks from the "to be processed" stock, thereby illustrating the dynamic evolution of the system. Finally, tasks rejected due to nonconformance, those necessitating rework, or those marked as unfinished tasks constitute the ReturnRate, serving as a flow between the WorkCompleted and Planned stocks.

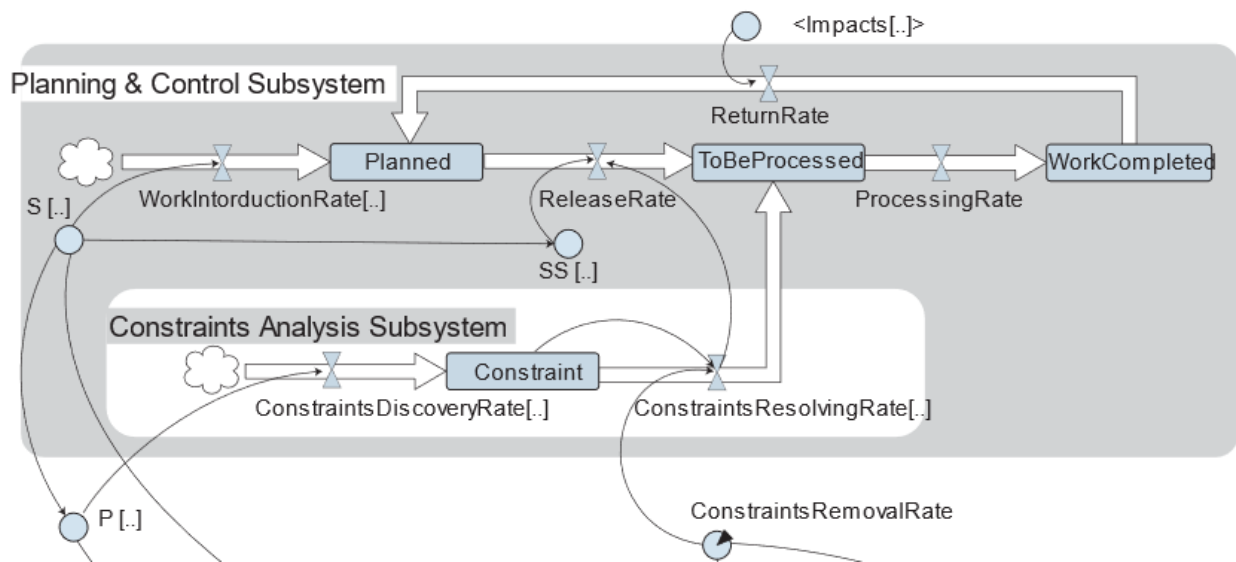


Figure 6-11 – Snippet of Planning and Control Subsystem

6.5.2. Constraints Analysis Subsystem

As clarified in the previous analysis, the constraints subsystem is significantly associated with the Making-Do waste (Amaral et al., 2022; Formoso et al., 2011; Leão et al., 2014). This subsystem encompasses a solitary stock, constraints, and two distinct flows, specifically constraints: DiscoveryRate and constraints: ResolvingRate. The influx of constraints intricately links to the prerequisites identified by the P function, which delineates task prerequisites (P1 to P6). According to the input data integrated into the Stock and Flow Diagram (SFD) model, we assume a ConstraintsRemovalRate of 1%, indicating the removal of 1% of the discovered constraints before execution. Subsequently, the ConstraintsRemovalRate flow contributes to the ToBeProcessed stock in the Planning and Control subsystem. This step stems from the fact that tasks liberated from constraints upon their removal are now deemed ready for execution and await resource allocation and management decisions to progress through processing them, while the processing rate determines how fast the production converts resources into value.

6.5.3. Making-Do Subsystem

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The focal point of this study revolves around the Waste subsystem, consisting of two pivotal components—namely, the Making-Do subsystem and the Making-Do Impacts subsystem. The Making-Do subsystem comprises a singular stock, Categories, and two flows, MD_GenerationRate and MD_ReductionRate.

The MD_GenerationRate is an array of functions that amalgamate various unresolved constraints (Koskela, 2004), denoted by the CAT dynamic variable (CAT1-CAT5). We ascertain these constraints through regression functions. Simultaneously, the MD_ReductionRate represents an array flow of Making-Do categories, illustrating the rate of resolution over time for Making-Do instances resulting from the removal of constraints determined by the parameter ConstraintsRemovalRate within the Constraints Analysis subsystem.

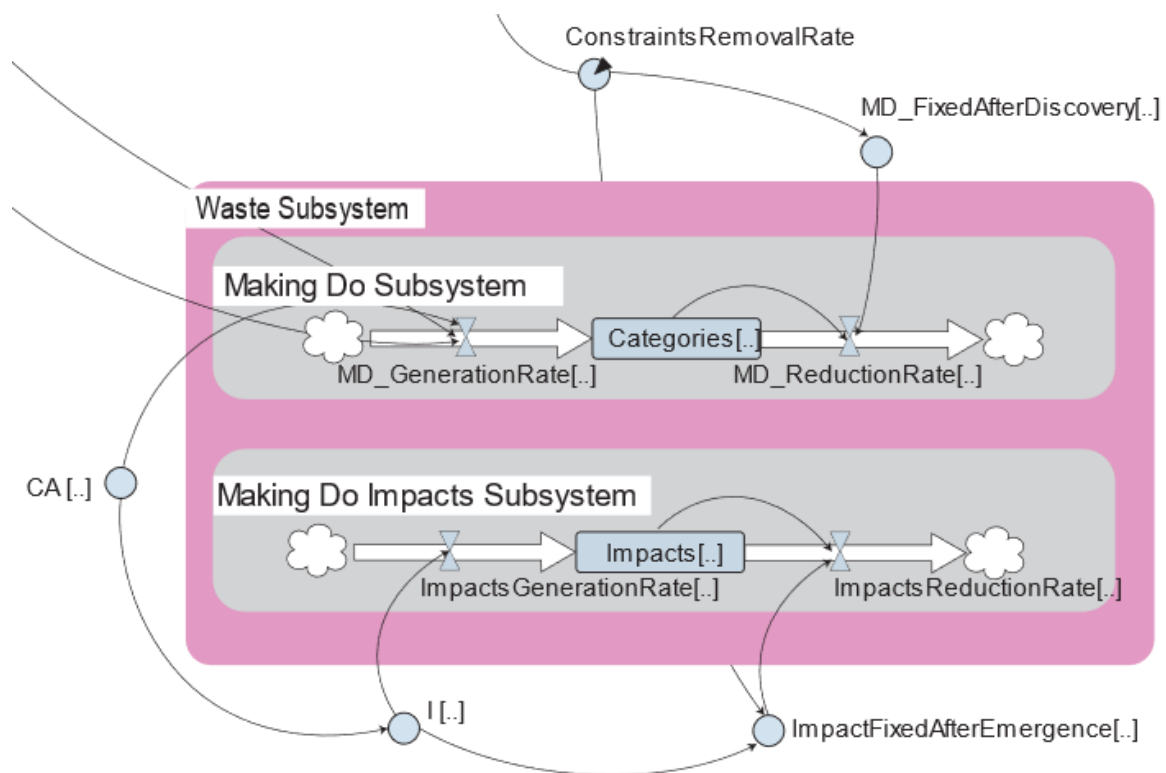


Figure 6-12 – Making-Do subsystem

The persistence of emerged MD categories without discovery or resolution governs the dynamics in the Making-Do Impacts subsystem. Following scholarly consensus (Amaral et al., 2022; Fireman et al., 2013a; Formoso et al., 2017), non-discovered MD categories contribute to adverse impacts on the production system, as symbolised by the Impacts stock.

The equilibrium or mitigation of this subsystem relies on the ImpactFixedAfterEmergence variable. This variable embodies a reactive approach commonly observed in traditional management, wherein

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the roles of planning and production/quality control are compartmentalised (Leão et al., 2014). This separation underscores the remedial measures taken after the emergence of Making-Do impacts, addressing and rectifying the adverse consequences during the traditional management process.

6.6. Simulation Results of MD emergence by using Traditional Planning Systems

6.6.1. Planning and Control Subsystem

The presented diagram, Figure 6-13, emanates from the simulation conducted within the framework of a dynamic system model constructed in the preceding sections. Upon examination of the graphical representation, it becomes evident that the pace of work progress exhibits notable acceleration in the initial stages of the simulation. However, a discernible decline in the number of completed tasks ensues as the consequential effects of resource constraints begin to manifest. Identifying rework necessities and unfinished tasks may also decrease completion rates, reducing productivity.

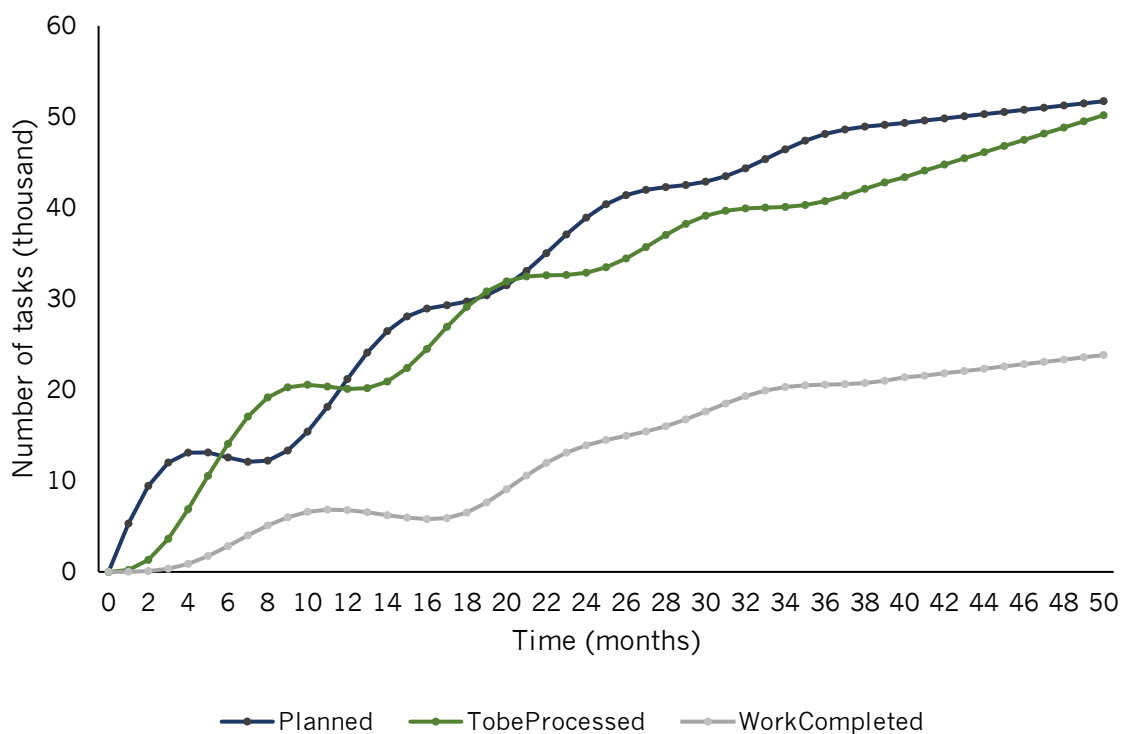


Figure 6-13 – Simulated for averages of planned, backlog, and completed tasks based on the traditional planning settings.

The initial values for planned work were determined using the average planning data from case studies (A, B, C) by running the system dynamic simulation for a time window of 50 months. The values of ToBeProcessed were computed by subtracting ProcessingRate and ReleaseRate (see Figure 6-10).

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These rates are obtained from MLRA equations in section 6.4. The observed fluctuation in the disparity between ToBeProcessed and Planned tasks is noteworthy, particularly in the initial half of the simulated period. This fluctuation can be explicable by the pronounced level of uncertainty inherent in project constraints during the project's nascent stages. Consequently, there is a propensity for the number of tasks awaiting processing to exceed the planned initial figures, reflecting the emergence of unforeseen constraints. As the project advances and more information becomes available, these initially unaccounted tasks are incorporated into the scheduled tasks.

However, the simulation reveals a pronounced widening gap between planned and pending tasks after the 20-month mark. Persistent unresolved constraints and tasks marked as "not ready for execution" contribute to this escalation. This manifestation underscores the inadequacy of traditional planning and control methodologies, characterised by reactive approaches, to effectively mitigate the deleterious impact of MD. Such methods tend to overlook or underestimate the existence of these inefficiencies, occasionally perceiving making-do as innovative in the short term, only to realise its long-term repercussions in the form of wasteful activities that impede overall production efficiency.

6.6.2. Simulation results of MD cases categorised into Phases and Substages

Figure 6-14 illustrates and depicts simulations of the number of project phases and tasks affected by MD incidents. The results reveal that during the initial months of the phases, the incidence of discovered MD was nearly negligible across various stages, including S1: structure, S2: walls and panels, S3: fixtures and fittings, S4: cladding and finishing, and S5: work completion. The simulated system dynamics showed that the accumulative number of MD cases encountered in the cladding and finishing phase registered the highest number, particularly involving panels, masonry, and painting tasks.

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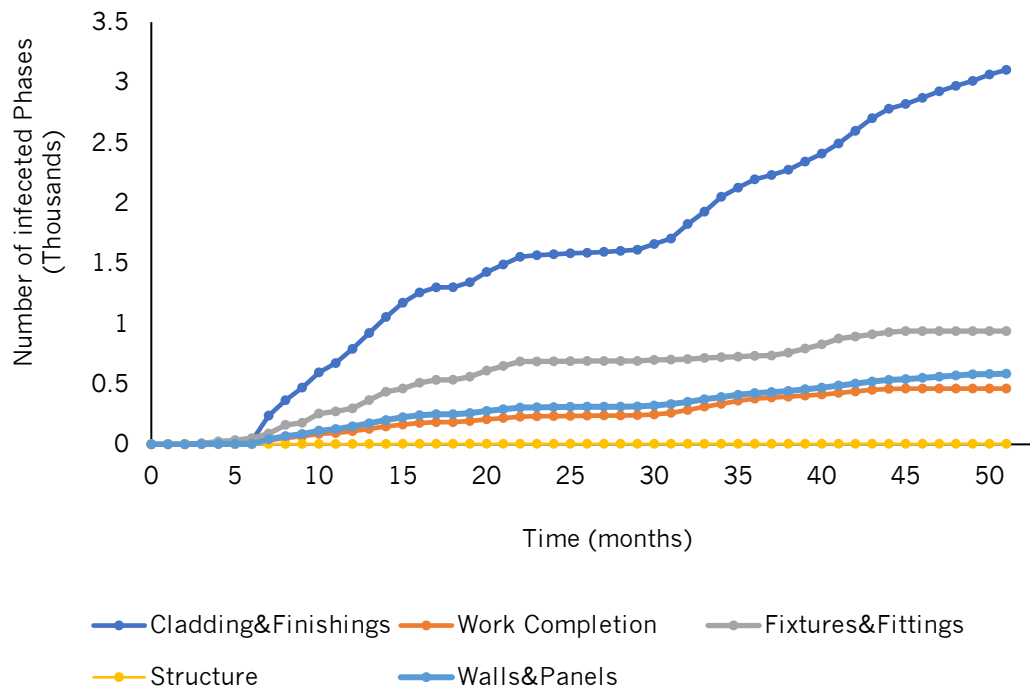


Figure 6-14: System dynamics simulation for project A stages infected by MD incidents.

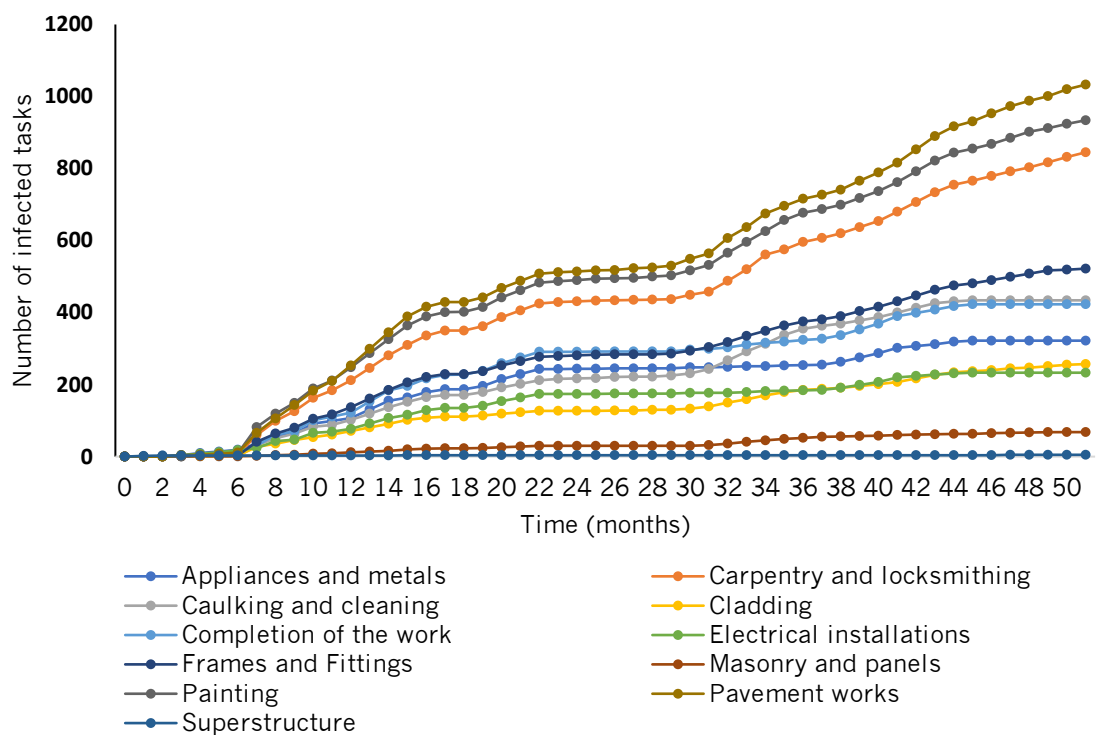


Figure 6-15: The accumulated number of simulated tasks included MD incidents.

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Figure 6-16 and Figure 6-17 delineate the variances between simulated and observed data.

Figure 6-16

Figure 6-16 shows the most notable variances in the work completion, fixtures, and fitting stages, recording values of -4 and 3, respectively. Similarly, Figure 6-17 presents variances between observed and simulated data for the number of infected tasks, with the highest variances recorded in pavement works, carpentry works, and painting, measuring -4 and -3, respectively. Notably, the variance between simulated data using system dynamics and observed data is acceptable. This slight variance implies that the model has successfully validated its ability to simulate phases that include MD incidents and predict the number of tasks influenced by wasteful MD decisions.

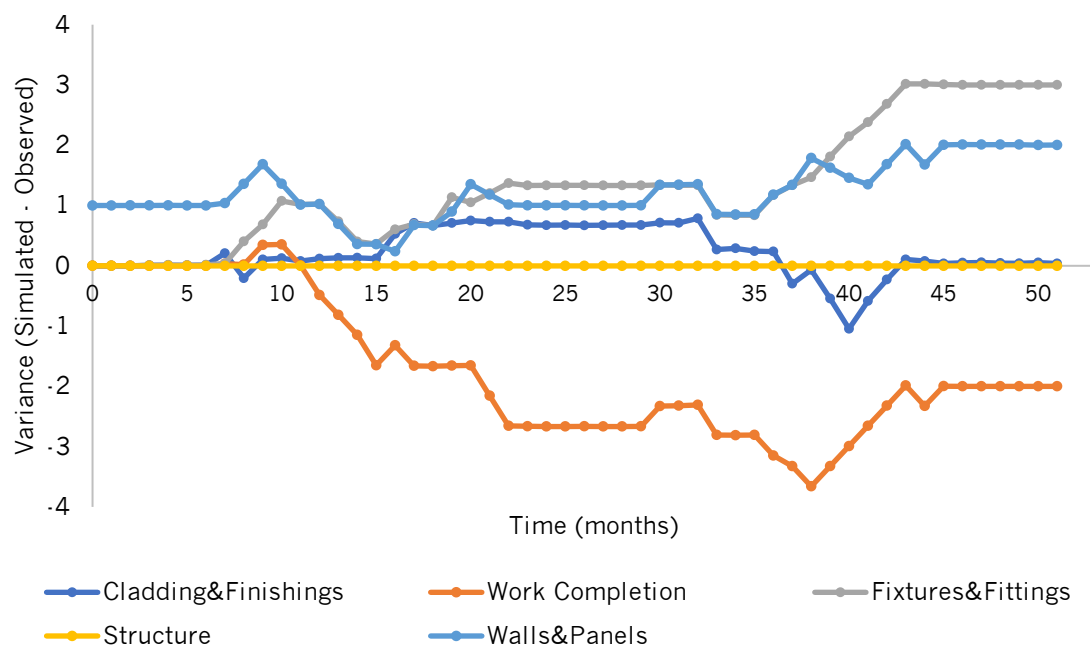


Figure 6-16: The difference between simulated (expected) and collected data for Stages infected by MD.

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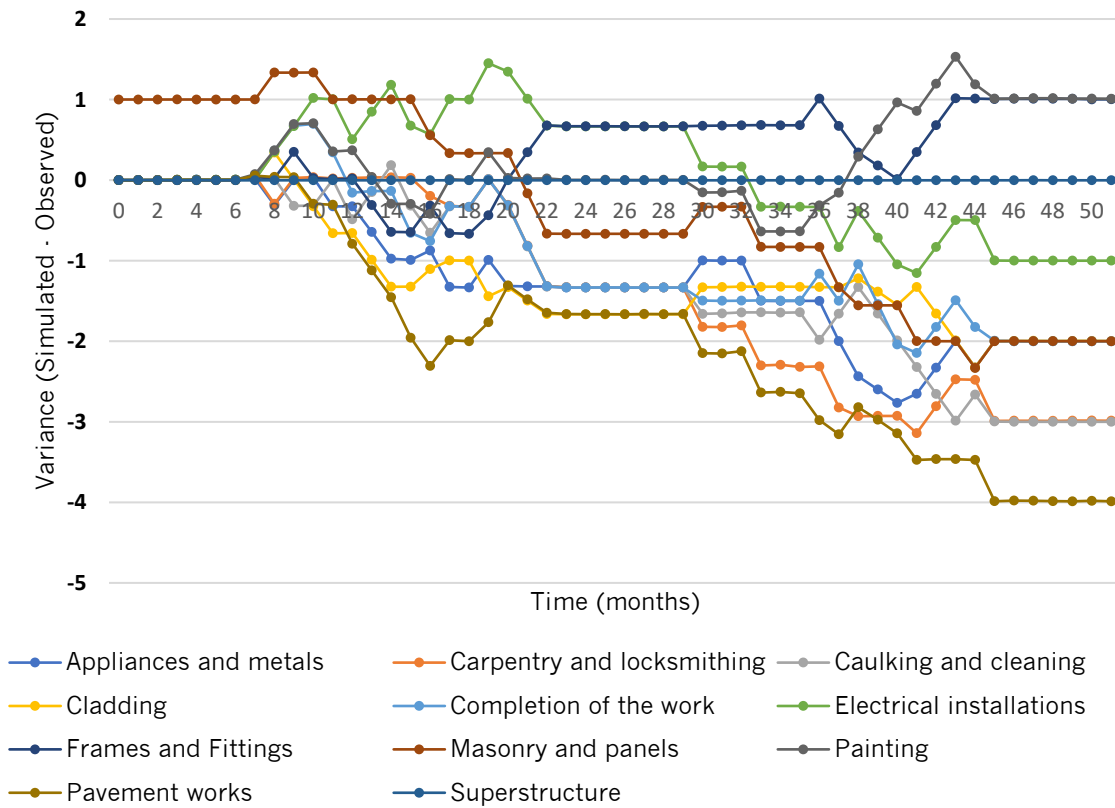


Figure 6-17: The variance between simulated tasks and observed data across time.

6.6.3. Constraints Analysis Subsystem

The constraints for construction tasks are 1- external conditions, 2-information, 3- interdependent tasks, 4- labour, 5- materials and components, and 6- space. Labour, Materials and components, and Interdependent behaviour appeared to be the highest in the simulation when the number of constraints/tasks reinforced exponentially at the simulation's beginning and then stabilised at well below 10% of total tasks, as shown in Figure 6-18. At the same time, the External Conditions and Space prerequisites were the minor constraints found in the studied cases.

6. Mathematical modelling for the LPS-BIM and MD systems

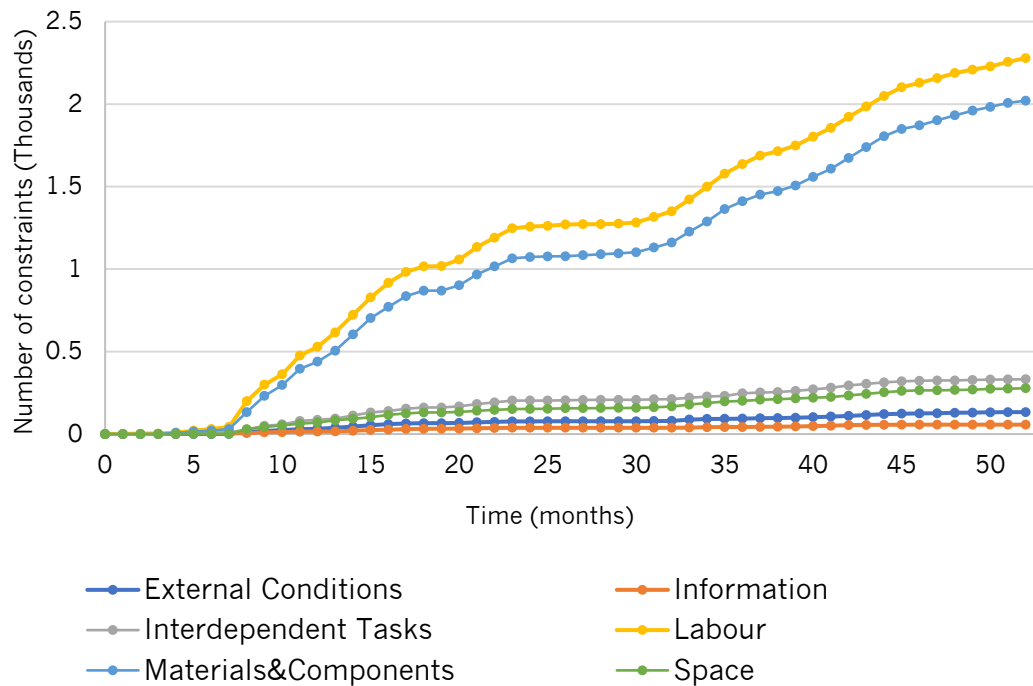


Figure 6-18: Simulation results for the number of constraints Case A.

Figure 6-19 illustrates the variances between observations and simulations of constraints encountered in the project, with the highest variances recorded for Interdependent Tasks, followed by Space, Materials, and Components. Notably, the depicted variances diminish during the long-run simulation, affirming the utility of the proposed model for the constraints analysis subsystem.

6. Mathematical modelling for the LPS-BIM and MD systems

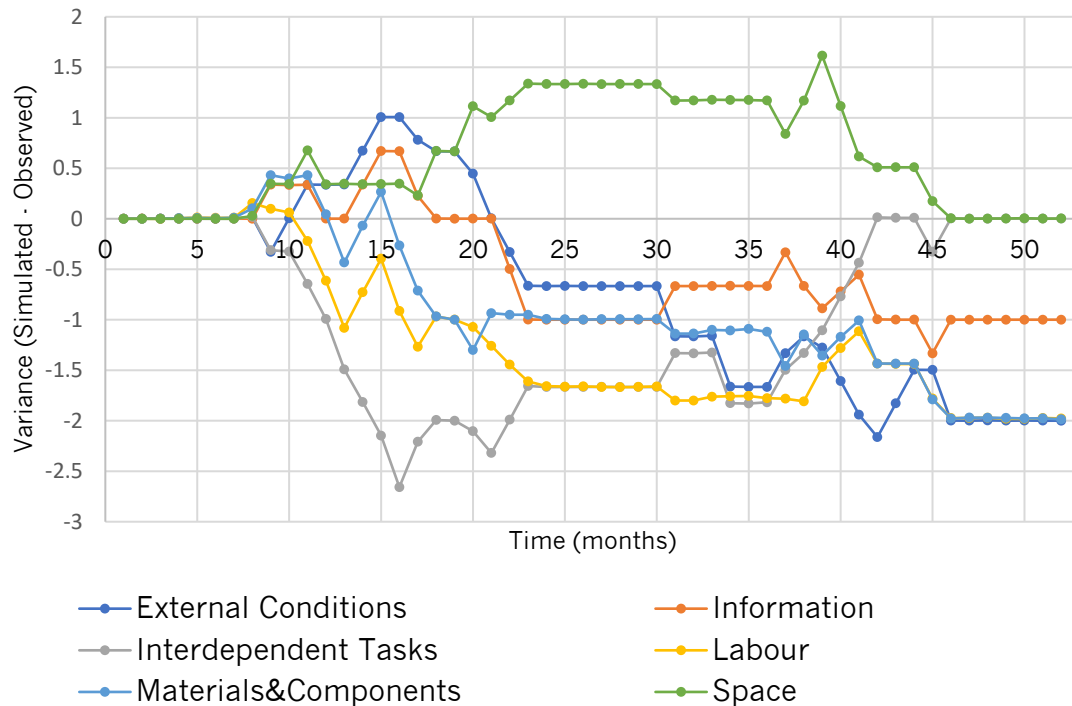


Figure 6-19: The variance between simulated constraints and observed data across time.

6.6.4. MD Subsystem

The categories of MD in Figure 6-20 include 1) Components Adjustment, 2) Tasks Sequencing, 3) Access and Movement, 4) Workspace, and 5) Equipment and Tools (Formoso et al., 2011). In alignment with the observed data, the simulation results indicate that the highest recorded category is Component Adjustment, followed by Sequencing. This result underscores the developed System Dynamic Model's need to enhance material management and planning. Furthermore, it emphasises the importance of meticulous investigation into the sequencing of interdependent tasks during the planning phase to ensure the smooth execution of tasks.

6. Mathematical modelling for the LPS-BIM and MD systems

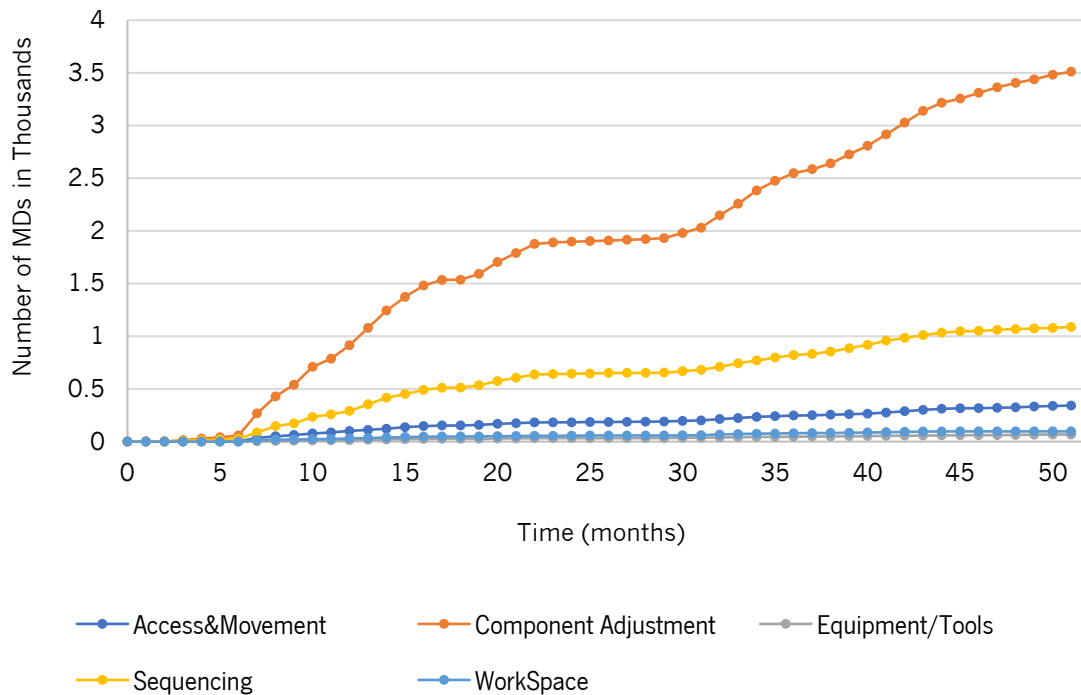


Figure 6-20: Simulation results for the categories of MD encountered in Case A.

The variances between observations and simulations of MD categories encountered in the project are depicted in Figure 6-21, with the highest variances recorded for "Components Adjustment," followed by "Accesses and Movement" and "Equipment and Tools." Notably, the illustrated variances decrease during the long-run simulation, affirming the utility of the MD subsystem model in predicting the categories of emerging MD. This trend suggests that the model effectively captures and simulates the dynamics of the "Components Adjustment," "Accesses and Movement," and "Equipment and Tools" categories, contributing to its reliability for forecasting potential MD occurrences.

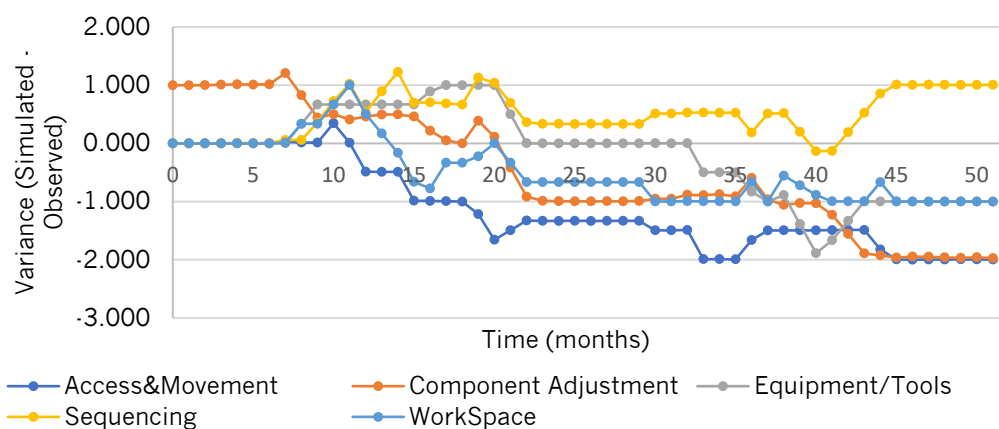


Figure 6-21: The variances between observed and simulated MD categories.

6. Mathematical modelling for the LPS-BIM and MD systems

6.6.5. The Simulation Results of MD Impacts System

Figure 6-22 presents the results of simulated waste impacts directly or indirectly caused by MD decisions in Project A. Consistent with the observed data, and rework constitutes the highest non-value activity resulting from MD, followed by decreased productivity and quality deviations. The resemblance in the patterns between simulated and observed data indicates that these impacts are interdependent. Therefore, there is a need to investigate and understand the relationships among these impacts to enhance the overall understanding of how MD decisions influence and propagate waste in the project.

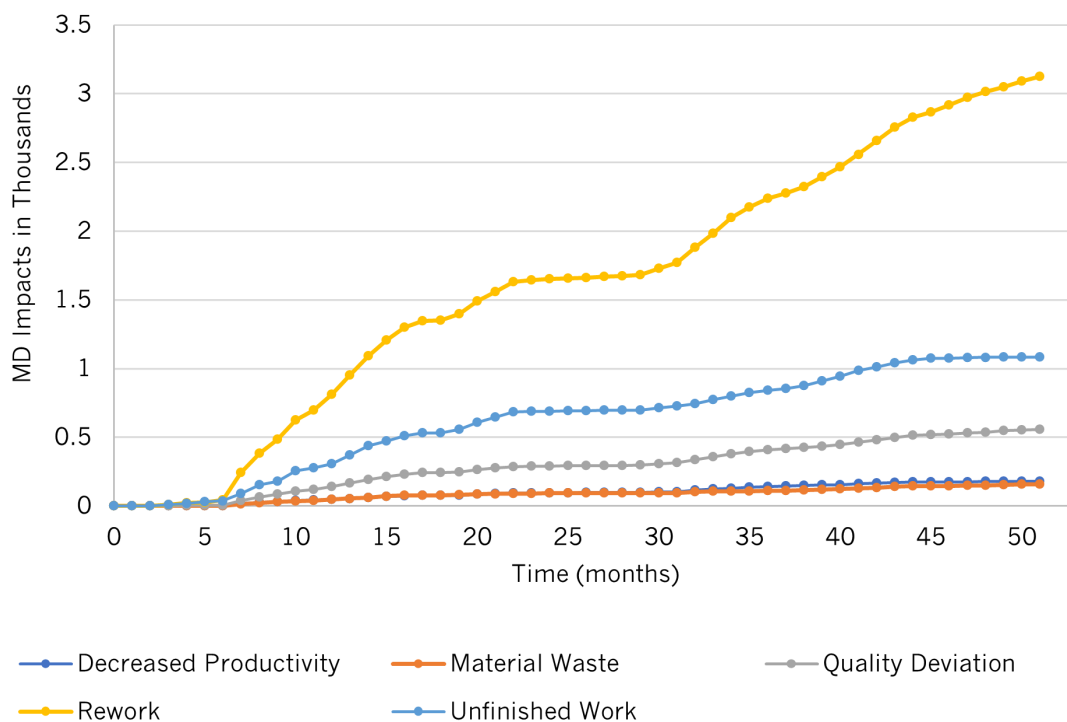


Figure 6-22: Simulation of MD impacts on the production system.

The variances between observations and simulations of MD impacts encountered in the project are depicted in Figure 6-23, with the highest variances recorded for Unfinished Works, followed by Material Waste and Quality Deviation. Significantly, the illustrated variances decrease during the long-run simulation, affirming the utility of the MD subsystem model in predicting the impacts of emerging MD. This trend indicates that the model effectively captures and simulates the dynamics of MD impacts, enhancing its reliability for forecasting potential occurrences of MD and their subsequent implications on Unfinished Works, Material Waste, and Quality Deviation.

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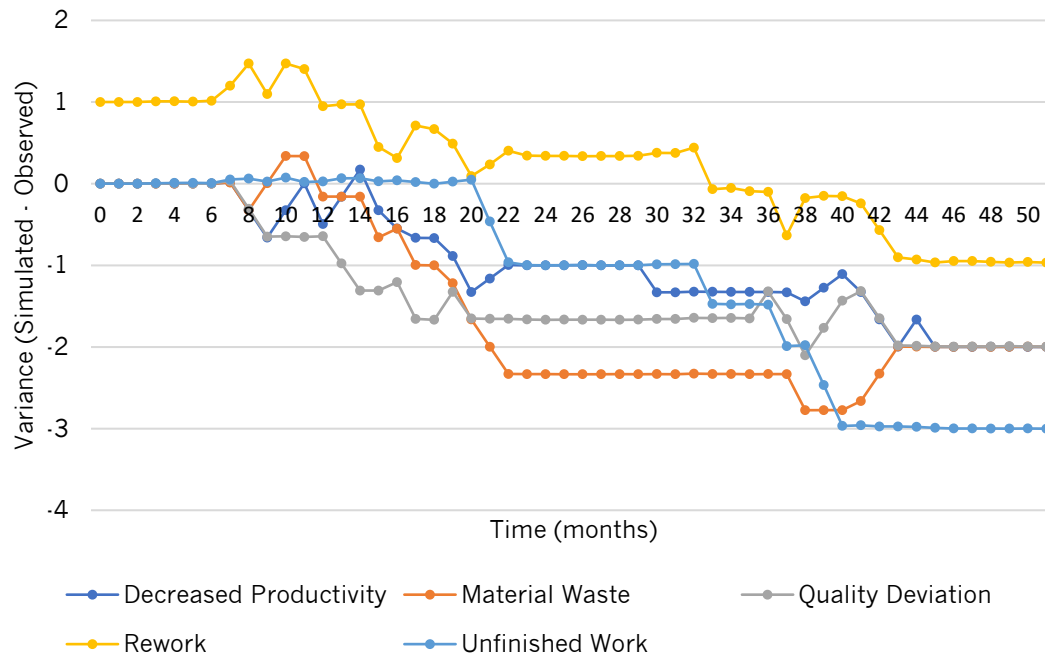


Figure 6-23: The variance between simulated and observed impacts across time.

6.7. Discussion

This chapter provides the underlying mathematical using a case study research method to explore various relationships among trades participating in construction projects (12/14), construction phases (5/6), construction constraints (6/8), MD categories (5/7), and MD impacts (5/8). Data was gathered from three projects in Brazil and France. Initially, association tests were conducted to examine the significance of the association between prerequisites and MD categories and whether waste generated is significantly associated with MD categories. The associations were found to have significant interdependence between the studied variables, and further investigation was recommended. That confirms that MD practices can be significantly controlled by eliminating the extant constraints during production planning and control due to formalising task assignments, execution, and delivery.

Multiple regression models were created to quantify these relationships within a system dynamic modelling framework. Based on these mathematical models, a system dynamic model for traditional planning and control settings was developed, focusing on four subsystems: 1) the planning subsystem, 2) the WIP subsystem, 3) the constraints subsystem, and 4) the MD subsystem by assessing several technical factors of MD waste.

6. Mathematical modelling for the LPS-BIM and MD systems

The proposal presented in (Amaral) has been fully confirmed for seven criteria: CAT 1, CAT 2, CAT 3, CAT 4 and CAT 5. Although these research findings align with the Amaral proposal, two MD categories were removed because their significance is relatively low compared to the five confirmed categories.

Concerning other MD mitigation criteria, system dynamics models can support their assessment in two different ways: by providing some information for the schedule progress (such as the amount of planned, work in progress, and finished works) – dynamic subsystem 1- or the work accumulation over time, the pace of production and planning reliability; by exporting Schedule specific information to dynamic analysis (required to initiate the change with the predetermined feedback loops). The utilisation of traditional planning and control settings can be included in modelling the last planner system's dynamic variables, but additional factors should be embedded to simulate the effect of the constraints analysis parameters (Ballard, 2020). Finally, the planned tasks' completion rate requires using resources and productivity data to assess the real-time task completion rate from the WIP calculated in the dynamic system. When facing the presented process with the traditional model to perform a waste analysis or address production inefficiencies, the most noticeable advantages are:-

- Accurate planning modelling: all the project stages and tasks can be modelled together, avoiding redundancies or omissions. Precise schedules contain all the construction phases, which can be broken down into substages and extracted to analyse MD practices and emerging waste comprehensively.
- Constraints characterisation for all the project stages and substages – the construction team can add or remove specific characterisation to the constraints found in the project, according to Koskela (2000). From arrays, functionality in the Anylogic software package can create all the constraints to be analysed in the dynamic system. The planning and control subsystem can change accordingly, and it contains the necessary relationships for MD analysis.
- The MD subsystem is developed similarly to constraints, which were characterised with specific modifications to accommodate the MD behaviour– the impact of constraint removal is high on the MD subsystem according to the simulation. Since all MD categories and their impacts were carefully prepared, defined, and simulated in the system dynamic model, they can be used as a decision-making tool to reach a limited number of MD incidents and impacts of MD practices.

By revealing the dynamic nature of MD, the proposed system can significantly inform the planners to uncover and eliminate MD compared to linear and traditional processes. There is no need to reinitiate the modelling process once the change has been applied; also, collaborative modelling opportunities

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can be enabled once the model is shared in the cloud. Even people with limited knowledge of SDM and LPS could understand and interact with the developed SDM, which may increase engagement and awareness in the decisions that can lead to MD practices.

However, there are some drawbacks to this process. It is possible to highlight the lack of any social dimension in the analysis and the need to create regression models and extract schedule data for an accurate MD prediction. This task must be formalised in a way that allows users to interact with the developed model and also allows them to learn about the concept of MD. The current waste management frameworks require a dynamic analysis of construction waste.

Considering the uncontrolled environment of the construction site and the strategic goal of decreasing MD practices, five strategic priorities should be added to the SDM according to the survey results in Chapter 5. Table 6-11 classifies these strategic priorities according to Integrated Lean Project Delivery (ILPD) stages, and each cell represents a dynamic variable that should be modelled in a system dynamic modelling. These priorities are identified in Table 6-11: 1) increasing the level of detailed integration between production and production information: this objective aims at securing continuous information flow with high automation capabilities, level of product and process integration, and interoperability between different disciplines. 2) Accelerating adaptation of the organisation towards LC and LPS: this strategic priority puts all the organisation's efforts together to provide preventive mechanisms to increase the participant's pace in discovering errors and waste causes (waste discovery rate) before the occurrence so the waste discovery rate was stated as a system parameter connected with *Adaptation* parameter. 3) Encouraging collaboration on MD incident resolution: This objective mainly aims to gain the collaborative advantage of LPS-BIM in applying LDM for early error prevention and providing collaborative designs for operations regarding the impact on MD elimination. 4) facilitating a collaborating constraints analysis within short- and long-term planning can be a parameter in dynamic modelling software to measure the process of constraints analysis indicator for project planning, which is affected in the design stage by design schedule pressure. In contrast, the variables for the construction stage are constraints, discovery rate, and construction schedule pressure. 5) Providing an active feedback mechanism for MD management is necessary for MD mitigation. The dynamic variable that should be considered in SDM is the Level of MD awareness, which is influenced by the MD impact ratio (in LDM, LSCM, and LC).

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Table 6-11 – LPS -BIM model parameters

Priorities	Model Parameters	LDM	LSCM	LC
1	Increasing the level of detailed integration between production and production information	Automation of Design	Design error ratio Design efficiency	Accuracy of resource estimation
2	Accelerating adaptation of the organisation towards LC and LPS	Level of Adaptation		Waste discovery rate
3	Encouraging collaboration on MD incident resolution	LPSBIM-based collaboration	Design Rework Discovery	Production modelling Communication on site
4	Facilitate constraints analysis within short- and long-term planning	Effectiveness of project planning	Design Schedule Pressure	Construction constraints discovery Construction schedule pressure
5	Active feedback mechanisms for MD management	Level of MD awareness	MD impact ratio	MD impact ratio

6.8. Conclusions

The system dynamics model offers profound insights into complex project management challenges, such as MD and its impacts. This chapter employs a case study methodology to illustrate the dynamic structure of MD in construction projects, conducting an in-depth analysis to identify the influence of technical factors on MD and their impact on production efficiency in terms of non-value-adding waste. The system dynamics model assists construction planners and teams in making informed decisions during planning, minimising the adverse effects of wasteful MDs, and guides them in planning constraints analysis sessions. This chapter is crucial for understanding and modelling dynamic phenomena like MD, aiming to derive policies for mitigating MD through planning and control countermeasures. The following chapter will discuss these countermeasures in detail, providing practical strategies for managing MD in construction projects.

Studying three projects, which include two newly constructed projects in Brazil and one rehabilitation project in France, led to training and formulating the mathematical model based on multiple regression modelling. This model is the foundation for stock and flow diagrams in a dynamic simulation of a system, encompassing two main subsystems. The first is the Planning and Control Subsystem, which tracks the status of planned activities, progressing from work introduction to intended to be processed, processed, and completed. It also outlines the role of constraints analysis within this subsystem, illustrating the impact of work marked as not completed. The second subsystem is the Making-Do Subsystem (MD Subsystem), which focuses on making-do activities crucial for understanding and addressing inefficiencies. After simulating the formulated model, we identified vital parameters to eliminate the root causes of making-do waste. Two primary interventions proposed include enhancing constraints analysis by increasing the constraints removal rate and improving the MD identification and reporting mechanism to address making-do issues before they escalate into negative impacts on production. These measures aim to optimise planning and control processes, ultimately reducing the occurrence and effects of making-do waste in the projects studied.

Once again, this study contributes to knowledge by introducing a novel approach to modelling the Making-Do (MD) phenomena, utilising technical factors identified in previous chapters. The results underscore the ineffectiveness of reactive approaches suggested by traditional management theories in limiting the growth of MD. During simulations, tasks were initially completed quickly due to MD decisions, appearing to shorten time or reduce costs in the short run. However, as MD began to impact production in the long run, rectifying these issues took longer and proved counterproductive. Consequently, a preventive paradigm, such as lean construction, becomes essential.

The developed system dynamic model exhibited minor variances when compared with observed data. Accordingly, it provides an opportunity to build on this model and formulate effective policies based on existing

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Lean construction artefacts, such as the Last Planner System (LPS). These can be complemented by Building Information Modelling (BIM), as discussed in earlier chapters of this thesis.

This analysis unveiled that relying solely on technical factors is insufficient for constructing a comprehensive understanding of the structural framework of MD waste management; therefore, social factors are necessary. Additionally, there is a need to broaden and explore the constraint removal and MD discovery rate by adopting different management approaches. Furthermore, the developed model did not illustrate the interrelationships among MD categories or different MD impacts. Further exploration of these interdependencies is required to enhance the reliability and generalisability of the proposed model.

On the use of data collected from the QuizQuality tool, there is a need to acknowledge that the data collected is limited because it relies on one data source only but on three projects with three different companies. For instance, the QuizQuality tool mainly captures the formally filed quality problems and may not afford a complete picture of “making-do” practices in construction projects. These might include the strategies that employees adopt to do things in a way that was not initially planned and informal practices, both of which might be quite common but will in all likelihood go unrecorded – and therefore unmeasured – since they are not part of the formal plans.

This chapter introduced a novel mathematical model for MD in the construction industry, offering awareness of its categories and impacts. The subsequent chapter will further develop the proposed system dynamics model by integrating socio-technical factors through the LPS and Building Information Modelling (BIM) to assess their efficacy in mitigating adverse MD decisions. The following chapter will aim to optimise the model complexity for scalability by focusing on a limited set of scenarios that cover a range of potential mitigation decisions. That would focus on targeted analysis and reduce the need for extensive simulations.

7. Simulating Dynamic Influences of the Last Planner System and Building Information Modelling on Mitigating Making-Do Waste

Since traditional planning and control methods fail to address the problem of proceeding with tasks without screening for potential constraints and continuing execution without acquiring their suboptimal inputs forming MD practices, this chapter aims to diagnose the impact of the strategies of LPS and BIM to limit these phenomena. This aim is streamlined into three objectives: 1) to expand the proposed SDM in the previous chapter to human resources, as well as the impact of schedule pressure and cost related to making-do practices. 2) to incorporate the key dynamic factors that constitute LPS and BIM strategies, 3) to simulate what-if scenarios of each level of LPS-BIM and measure their impacts on MD mitigation. The study quantitatively formulated a causal structure for the three concepts of LPS, BIM, and MD waste, which embedded mathematical relationships among them into a stock and flow diagram (SFD). The case study methodology was applied to test and validate the constructed model. Finally, recommendations that form a lean-based policy to mitigate MD at source are proposed.

Except for some changes executed for the formatting and organisation purposes of global information in this document, this chapter integrally presents the work:

Karaz, M.; Teixeira, J.M.C.; Amaral, T.G.d. Mitigating Making-Do Practices Using the Last Planner System and BIM: A System Dynamic Analysis. **Buildings** **2024**, *14*, 2314. <https://doi.org/10.3390/buildings14082314>

7.1. Introduction

Production planning and control entail integrating technical and social factors, as Baldwin and Bordoli (2014) posited. Within the Last Planner System (LPS) hierarchy, the lookahead process emerges as a pivotal mechanism for aligning the master plan with the weekly work plan. However, achieving a comprehensive understanding necessitates the incorporation of social-technical dynamics within the workplace milieu. This understanding entails conceptualising production planning and control as a multifaceted negotiation and communication process wherein human attributes such as flexibility, adaptability, learning, and intuition assume critical significance in effectively implementing LPS Aslesen and Bertelsen (2008).

This chapter intends to systematically model and simulate the dynamics of countermeasures of LPS and BIM to address MD waste within construction projects. This chapter seeks to predict and assess the outcome of different activities that may involve the utilisation of LPS and BIM in identifying constraints, occurrences of MD incidences, and recognition of other forms of waste produced at the end of the production line. In particular, it seeks to explain the rate of identification and deletion of MD categories concerning the implementation of LPS and BIM. In addition, the study aims to ascertain the extent to which LPS and BIM help reduce general construction waste such as rework, quality control issues, incomplete work, materials wastage, productivity, and safety loss. Further, it explores the part performed by collective specific social aspects such as collaboration, adaptation, knowledge, and particular technical factors, including productivity, resources management, and BIM functionalities, in producing MD incidents in the construction process.

The chapter is structured as follows: The second is designed to justify the case study's choice and describe the methods used in system dynamics modelling. The third section aims to determine the crucial data for combining LPS and BIM to reduce MD waste assessment with the help of criteria and mathematical relations in chapter five. The fourth section also explains how LPS and BIM work in synergy to help reduce MD and the nature of their interaction. The fifth section mimics this interaction of the studied variables and investigates various LPS-BIM parameter interactions. The sixth section demonstrates the applicability and effectiveness of the developed system dynamic models using selected case studies. The last section summarises the key findings, discusses implications, and delineates opportunities for future research.

7.2. Methodology

7.2.1. Overview of the research design

The research design depicted in Figure 7-1 was adapted from the SDM method outlined in the preceding chapter to align with the collected data and the chosen validation approach. The research methodology comprises four key stages: data collection, analysis, system dynamics modelling, and validation. The primary method employed for data collection, aimed at developing a rating system for LPS-BIM, involved a questionnaire survey, as detailed in Chapter 5. The chosen case study, a condominium project in Brazil, was utilised to ascertain commencement and completion dates, identify trades involved in MD-affected processes and delineate the phases and processes encompassing MD incidents.

Subsequently, a quantitative research approach was adopted to analyse the gathered data employing Minitab Software. Three analytical methods, namely one-way ANOVA, chi-square, and multiple regression analysis, were used to assess the internal consistency of the collected data. Additionally, these statistical techniques facilitated the development of mathematical models via regression analysis, integral to the subsequent construction of the Stock and Flow Diagram (SFD).

Thirdly, in the Anylogic® professional 8.7.11 system, dynamic modelling was employed for data processing, commencing with the conceptualisation of production and planning control functions, alongside integrating MD waste and other associated wastes in a Causal Loop Diagram (CLD). Subsequently, regression formulas derived from the data analysis stage and a project management model (Lynes, 2004) were utilised to construct the Stock and Flow Diagram (SFD). The dynamic model underwent validation through assessments encompassing dimensional consistency, sensitivity analysis, parametric variation, and extreme condition testing. Lastly, the D3M (Decision-making tool for Mitigating Making-Do practices) was introduced to formulate a lean policy to mitigate MD occurrences. The efficacy of this approach was validated through the case study method.

7. Simulating Dynamic Influences of the Last Planner System and Building Information Modelling on Mitigating Making-Do Waste

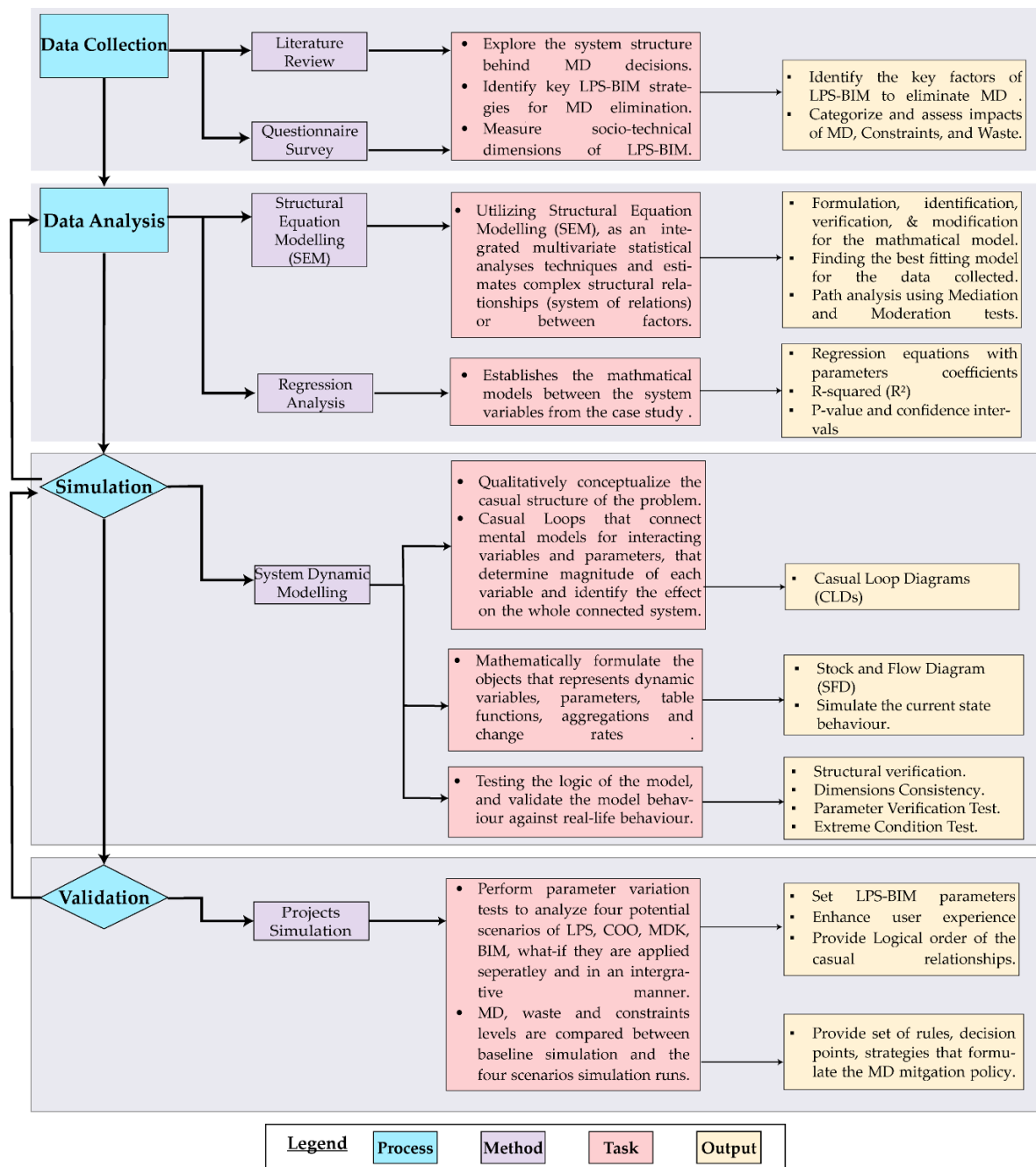


Figure 7-1 – The research design used for this chapter

7.2.2. Case Study

Yi's (2018) model is employed for this case study as an empirical investigation to explore the MD phenomenon within the context of construction projects. The absence of clear and distinct boundaries between MD and the construction context justifies using a case study approach. The selected case studies are aligned with the research objectives, primarily due to their explicit recognition of MD waste. These studies share common characteristics, are both involve condominium projects, and they are

7. Simulating Dynamic Influences of the Last Planner System and Building Information Modelling on Mitigating Making-Do Waste

relatively extensive constructions, with project A having a land area of 6,323.24 square meters and project B covering 2,912.28 square meters; iii) both projects are situated in Goiana state, Brazil, a factor expected to mitigate the impact of cultural, economic and resource differences between the compared projects. Table 7-1 provides a detailed illustration of the characteristics of each project.

The unit of analysis for the data collected is the number of activities influenced by MD practices and the number of unresolved constraints and impacts resulting from MD practices. Data extraction was performed through two secondary sources. The first source utilised a quality issue registry tool (QuizQuality), which records incidents of quality non-conformance and enables labourers and superintendents to report reasons for non-completion. The second method involved interviews to gather insights into daily routines, processes, and the participation of delegated teams in short-, medium– and long-term planning. The data collection followed a pre-established and validated protocol (Amaral et al., 2022; Amaral et al., 2020; Dos Santos et al., 2020).

Case A includes three towers with 196 apartments, each sized 45.4 square meters, with seven floors per tower and one designated elevator for each. The common areas comprise a party hall, a swimming pool and fitness zone, a playground, a multi-sport court, and a guardhouse complete with CCTV cameras and security systems. Additionally, the parking area is located outdoors with 33 parking spaces.

Case B consists of two towers spanning 31 floors and 210 apartments. The project features two floors of 265 indoor parking spaces, and the first two floors will be used for leisure activities and coworking areas, with three working stations, two meeting rooms, and collaborative places. Moreover, the buildings have printing services, a cafeteria, and spots for coffee breaks.

Table 7-1 - Comparative Overview of Selected Construction Projects A and B

Case A	Case B
	

7. Simulating Dynamic Influences of the Last Planner System and Building Information Modelling on Mitigating Making-Do Waste

Enterprise Code	M	N
Start and Finish Dates	03/2016-03/2021	08/2021-11/2024 (projected)
Project type	Construction multistorey condominium	Construction multistorey condominium
No of Towers	Three towers	Two towers
Floors /tower	7	31
No residential units	196	210
Constructed area (m ²)	28,420	30,603.51
Land use (m ²)	6,323.24	2,912.28

Projects Organisations

The owner of project A is a parent company of enterprise M, a holding company structured as a multi-functional team of administrative, architectural, mechanical, and electrical design personnel who come together to provide design and construction services for project A. These individuals step into more complex tasks that imply more responsibility, such as dealing with finances and keeping records. Under the hierarchy, the general manager would represent the owner and take the role of project manager, who would administer the contract in general. The role of the engineering manager initially taking the position of Site Engineer, mainly on behalf of the project owner, involves hiring staff and subcontractors at the early stages. Still, he has no prior experience in using BIM or Lean construction. At the same time, the architectural office of this firm manages design development, execution, and exchange based on the BIM methodology.

The owner of project B is a property developer, and the real estate group has a team of representatives administrative, financial, design, and execution teams. After a thorough assessment, the project was awarded to a construction management company that managed the contract and an architectural company to deliver and manage the project information. Under the hierarchy, the general manager would represent the owner and take the role of project manager, who would administer the contract in general. The role of the engineering manager initially taking the position of Site Engineer, mainly on behalf of the project owner, involves hiring staff and subcontractors at the early stages. Still, he has no prior experience in using BIM or Lean construction. At the same time, the architectural office of this firm manages design development, execution, and exchange based on the BIM methodology.

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Lean Construction Initiative

Both firms have implemented organisation and construction managerial strategies to improve construction site productivity and workflow. It has been the key to assuring a lean construction process similar to the Toyota Production System (TPS) and Total Quality Management (TQM), which had been implemented to address the MD culture on the construction sites. In addition to this, they employ the BIM-enabled app "QuizQuality" to store quality problems and waste data, including MD waste. Nevertheless, the Last Planner System partially operated at a medium level, having an informal engagement of stakeholders.

BIM Initiative

Enterprise M internally hired a certified BIM team to oversee the design, including 3D visualisation, BIM coordination, quantity take-off, 4D planning simulation, and 5D BIM integration. Virtual Construction (3D BIM) is used to increase the understanding of the project and the cooperation between the contractors, resulting in fewer misunderstandings. BIM coordination eliminates clashes that are difficult to detect in 2D drawings, decreasing the need for reworking. The quantity take-off is a basis for accurate cost estimates and improves the estimation process. 4D BIM facilitates virtual construction, allowing one to analyse the effectiveness of the execution plan and site logistics—5D BIM embeds budget processing with 3D modelling, enabling cost analysis and value optimization.

The enterprise N authorised a BIM consultant to provide adaptable project design delivery with the help of BIM technology that includes parametric modelling, cost estimation, coordination and compatibility evaluation, structural analysis, and clash detection. The consultant took part in the technical meetings dealing with the best design solutions, also participated in the implementation team's process of obtaining according to the local requirements and regulations planning authorities' approval, organised the information flow between the different disciplines, institutions, and authorities on various levels of the project lifecycle and set the processes for design control, verification and monitoring the information deadlines, thus optimised the information flow for construction engineers. Besides, the subcontractor performed clash detection analysis to determine the possible conflicts between disciplines and objects during construction in different phases. Furthermore, such a practice ensured compliance with structural codes through rigorous application of structural design and analysis using BIM workflows. Among the many benefits, BIM workflow also affects the development stages of the construction company and its supply chain. It connects them with the BIM model for budgeting and planning.

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Waste elimination initiative

Process and product quality problems are the main concerns of both companies. In alignment with quality management systems, Enterprise N has attained certification under the NBR ISO 9001:By 2015 norm. However, Enterprise M has concordantly been following the accepted norms of the PBQPH, the federal certification authority for the construction sector in Brazil, along with the ISO 9001 certification standard. The teams faced construction waste and operational efficiency issues as they were clear on rework or highly increased non-value-added rates and materials). In addition, both projects exceeded their budgets and were extended in duration due to unexpected waste. Thus, following along, crucial remedial measures had to be taken at the planning and control stage to provide comprehensive elimination of construction wastage, encompassing material wastes of various types and non-value-added waste. The latter is an essential part of the lean construction doctrine and may involve overproduction, long waiting times, problematic rework instances, quality deviation, rework, and unfinished works.

7.2.3. Development of the dynamic simulation model

Based on the proposed SDM model in Chapter 6, this chapter adds the critical factors of LPS and BIM that tend to mitigate MD practices. The developed Dynamic Making-Do Mitigation Model (D3M) aims to target problems that prevent the MD by early discovery and removal of construction task constraints. The developed model comprises the following steps:

- Mathematical model development:
 - Following the method used in Chapter 6, Multiple Linear Regression Analysis (MRA) represents the mathematical background for the relationships between stages, substages, trades, constraints, MD categories, and MD impacts. This data is supplemented by quality application data, labourer data, and master schedules, which were determined using CPM and shown in Gannt charts (Appendix II).
 - Following the method used in Chapter 5, based on a questionnaire survey performed, the Structural Equation Modelling (SEM) method was the backbone for the inclusion of a mathematical model for social factors; their social parameters were allocated to determine the influence of LPS and BIM strategies to mitigate MD and its impacts.
- The dynamic variables are collected about the maximum number of tasks in each stage and substage, the maximum number of trades, and the maximum number of workspaces, besides

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the dynamic variables that perform mathematical functions and inputs as described in detail in (Appendix IV).

- Dynamic analysis will be running to investigate the value of each stock across the running time, which is 52 months. These stocks include planned stages, planned tasks, completed tasks, work in progress, completion rate, the number of constraints at each stage, and MD categorised into categories as revealed in (Chapter 4).
- The running system dynamic model will lead to simulation results, allowing the researcher to evaluate the impact of the modelled parameters (Simulated results vs. Actual project data). This evaluation will measure the model's correctness and consistency in representing the real world.

D3M could predict the number of infected tasks and MD incidents and quantify the impacts of MD. LPS-BIM comprises four main components: 1) Last Planner System, which contains social and technical dimensions; 2) BIM functionalities subsystem, including 4D planning, visual management, and clash detection.

- The Last Planner Parameters

According to the Last Planner System benchmark report, a partial implementation of LPS functions can lead to practical results regarding planning reliability and workflow. The social countermeasures include three aspects: collaboration by handling disagreement and interests among diverse parties, which requires ensuring a high level of coordination and enabling constructive and critical discussions; adaptation encapsulates local adjustment of LPS functionalities to fit the organisational structure and the context of the application; and networking. The technical factors are the most discussed in the literature, encompassing visual management, lookahead planning, weekly/daily planning, analysing trends, measuring planning system performance, and continuous improvement through systematic learning. Learning is shared at the point of work.

- Building Information Modelling (BIM)

Despite the use of BIM for planning and control in the current tools and the proposal of integration of BIM with the LPS, there is still a lack of research considering all the strategies to assist production planning and control in terms of waste reduction produced, where BIM still considered product-oriented rather than process-oriented (Dave & Sacks, 2020). Despite the

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potential benefits, BIM has not been comprehensively used to assist construction teams with information about task constraints and decisions for performing specific tasks (Etges et al., 2020). The existing lean construction policies still lack social factors used alongside BIM terminology. While adopting lean culture, its integration never addressed production waste reduction strategies.

7.3. Planning and Control System

This section details the dynamic components of planning and control subsystems using the stock and flow diagramming (SFD) method. This system is composed of four subsystems: 1) master, phase, and lookahead planning subsystem, which simulates the project planning and completion status; 2) constraints analysis function subsystem, which indicates the number of discovered and removed constraints; 3) construction productivity subsystem, this subsystem mainly focuses on converting the inputs of the project into processing rate in order to complete the project and includes the management strategies to avoid schedule delays, and 4) resources subsystem includes the dynamic variables of labors and location that contribute to the overall productivity.

7.3.1. Master, Phase, and Lookahead Planning

Figure 7-2 provides an overview of the workprogress subsystem using the stock and flow diagramming method. A customary initiation point for a planning system involves defining project goals, typically input by the user as a constant to provide an initial estimate for the quantities or number of tasks allocated to each stage. This input serves as the baseline value for the stages allotted throughout the project phases, while milestones dictate the progression from one stage to another and often serve as benchmarks for gauging the project's strategic-level performance. The primary determinant of change within the "stages" stock is the rate at which tasks are transitioned by the planning team from master planning to the "WIP" state for execution or advancement in planning. This rate of change is conceptualised as a flow entity denoted as "BackLogRate," measured in tasks per month.

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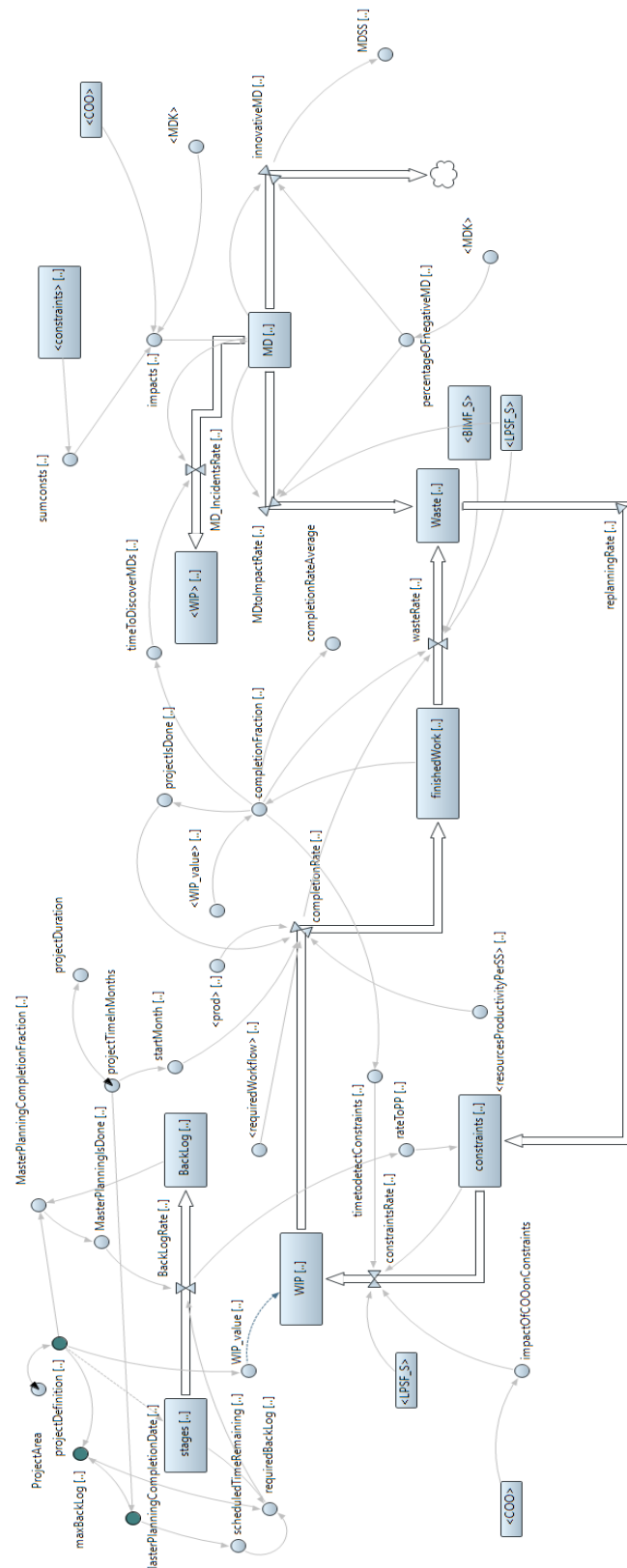


Figure 7-2 – Workprogress subsystem with MD and waste subsystems.

The magnitude of the "BackLogRate" is contingent upon the task counts within both the "stages" and "WIP" stocks. Specifically, when the number of tasks in "WIP" equals or surpasses the number of

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functions in the "stages" stock, the BackLogRate diminishes to zero. Conversely, if the task count in "WIP" falls below half of the tasks in the "stages" stock, the BackLogRate escalates to its maximum level, determined by user-defined constants.

Acknowledging that the "WIP" stock facilitates categorising the five phases from the "stages" stock into 11 work packages is imperative. This functionality aligns with the principles of the last planner system, advocating for the breakdown of projects into manageable, measurable, and controllable work segments. However, it is noteworthy that the SDM method does not accommodate the granular breakdown of work into operations and tasks due to the inherent abstraction level in SDM.

7.3.2. Constraints Analysis Function

The efficacy of constraints analysis is paramount in mitigating the adverse effects of MD practices. Its effectiveness is contingent upon two primary factors: the proportion of scheduled tasks within each phase, which influences the timeframe for identifying constraints, and the chosen production policy, whether it adheres to a pull or push strategy. Notably, when a push strategy is employed, there tends to be a higher incidence of encountered constraints later in the project, whereas the opposite is observed with a pull strategy. The functionality of constraints analysis directly impacts MD incidents and indirectly influences waste generation, as elucidated in Section (Quantifying MD Practices). The accumulation of unresolved constraints necessitates reevaluating and adjusting affected tasks to facilitate problem-solving discussions with the pertinent teams. Consequently, in this framework, the quantity of each constraint is integrated into each stage's stock, necessitating additional time for the re-planning processes in stages where constraints are identified but not resolved. Table 7-2 shows a table function that converts the workprogress percentage to the time needed to discover constraints in the project, and the graph shows that as the project reaches the end, fewer constraints are discovered; this table function is influenced by the uncertainty level inherited in the project plan.

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Argument	Value
0.0	5.0
0.1	4.5
0.2	4.0
0.3	3.0
0.4	2.0
0.5	1.0
0.6	0.9
0.7	0.8
0.8	0.7
0.9	0.6
1.0	0.5

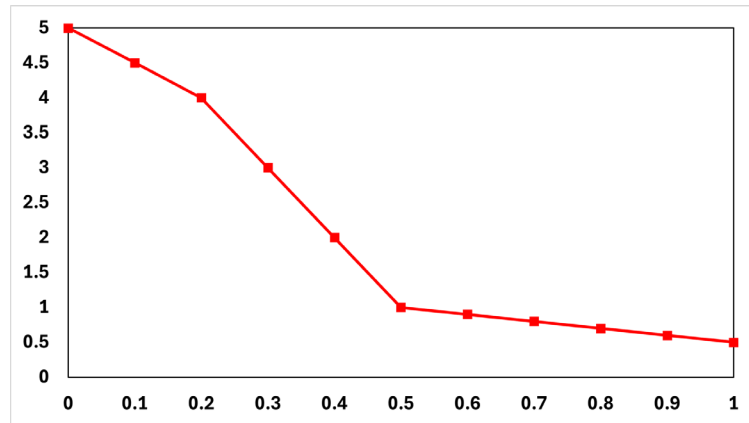


Table 7-2- Time to discover constraints with master planning completion

7.3.3. Construction Productivity factors

Finished Works Stock is one of the objective metrics for evaluating the change rate based on the number of MDs, which is calculated based on the resource productivity rate in processing tasks from ToBeProcessed stock. The rate influences this changing rate at which individuals complete tasks, which depends on the resource allocation by the resources subsystem and the productivity ratio (Thomas et al., 1990). Productivity is the ratio of total output to the sum of inputs, including items, for example, labour, material, equipment, energy, and capital (Equation 7.1). This equation sums the productivity levels in each workflow to determine the total project productivity; such definition should also govern the impact of space, as indicated in LBMS, which considers that operations should be seen as the movement of labour and equipment across locations. This research disregarded the output value of equipment and energy outputs due to insufficient data collected. However, their contribution to the total production was considered and subtracted.

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$$\text{Productivity} = \frac{\text{Total Output}}{\text{Labour} + \text{Materials} + \text{Equipment} + \text{Energy} + \text{Capital}} \quad \text{Equation 7.1}$$

In the literature, construction productivity is further elucidated as being influenced by various variables, including the availability of resources, workspace availability, the impact of schedule pressure, overtime, and fatigue. The dynamic equation (7.2), denoted by $\text{Prod}[\text{Substages}]$, is a mathematical representation of productivity, which calculates an array of actual productivity values for labourers in each substage from SS1 to SS11. In this research, the productivity variable is defined by the following endogenous variables: overtime, fatigue, limited available space, and BIM implementation (Porwal, 2013). It is acknowledged that productivity may be influenced due to the factors depicted in Figure 7-3.

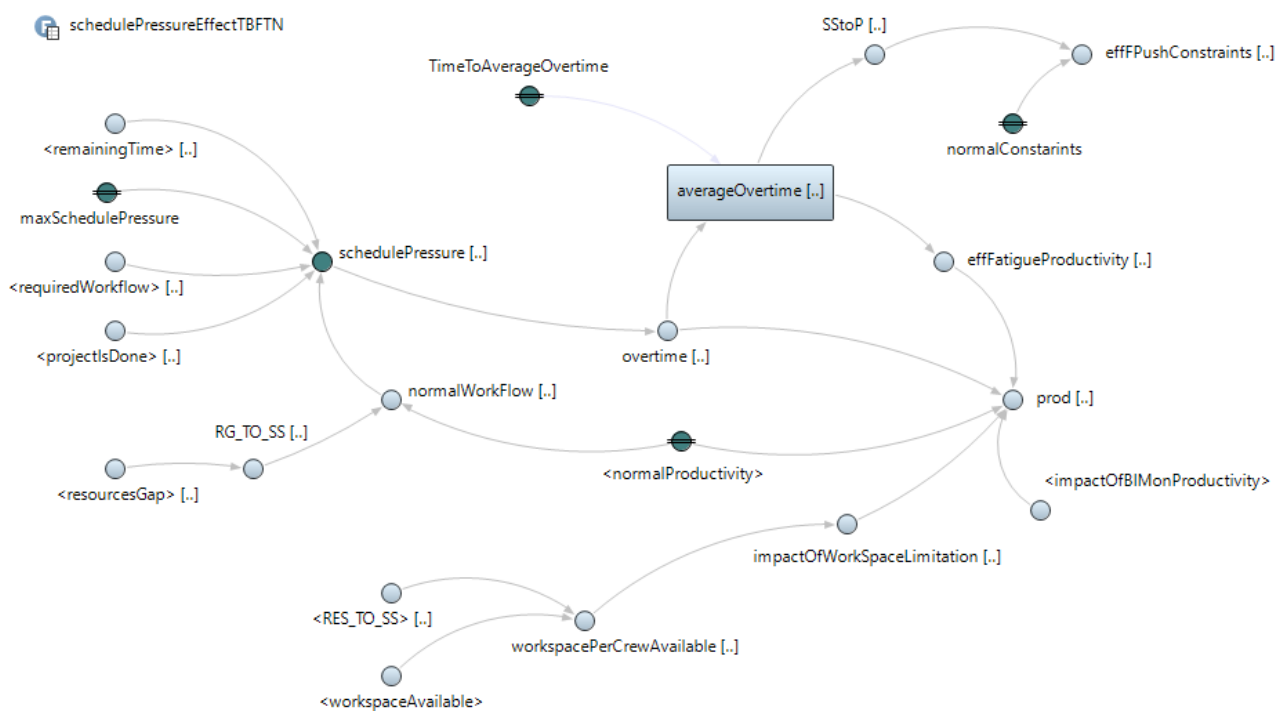


Figure 7-3 – The dynamic variables affecting the construction productivity.

$$\begin{aligned} \text{Prod}[\text{SUBSTAGES}] &= \text{effFatigueProductivity}[\text{SUBSTAGES}] * \\ &\text{overtime}[\text{SUBSTAGES}] * \text{normalProductivity} * \\ &\text{impactOfWorkSpaceLimitation}[\text{SUBSTAGES}] * \\ &\text{impactOfBIMonProductivity} \end{aligned} \quad \text{Equation 7.2}$$

A detailed description of the variables that affect Productivity is structured as follows:

- The impact of workspace limitation (*impactOfWorkSpaceLimitation*)

The influence of workspace limitation directly affects productivity by altering the ratio of resources and working shifts, thereby shaping the $\text{locationsUtilisationRate}$, which determines the number of occupied locations (Seppänen, 2020). Simultaneously, the available workspace is more

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accessible to be defined by `locationsUtilisationRate` as shown in Equations 7.3, 7.4, and 7.5, with its indirect impact on `locationsUtilisationRate`. The effect of workspace limitation on productivity is detailed within the table function as presented in Table 7-3 (Hewage & Porwal, 2011).

Notably, the `zidz` function prevents division by zero, where it returns a zero value in such instances, assuming that the value of shift hours is 4 hours.

`durationInHrs =`

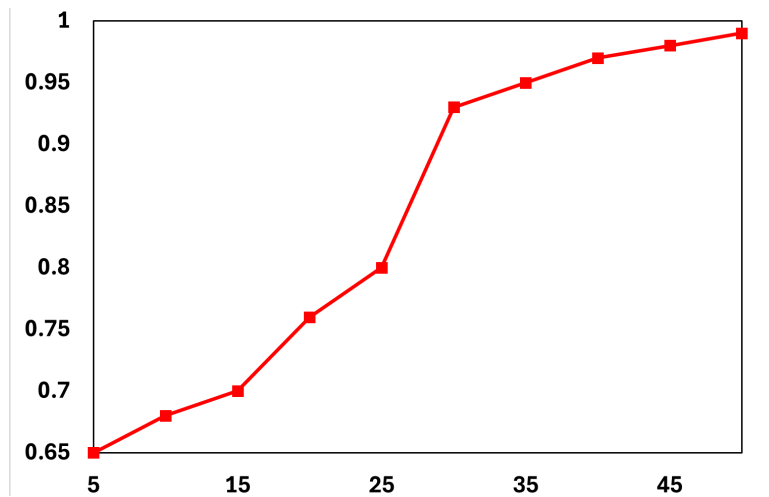
`zidz((zidz(ToBeProcessed.average()),resources.average())*240)` Equation 7.3
`, monthToHrs)`

`locationsUtilisationRate= durationInHrs / shiftHrs *` Equation 7.4
`occupiedLocations`

`workspaceAvailable= initialLocations - finishedLocations -` Equation 7.5
`occupiedLocations`

Table 7-3 - Lookup function of the impact of workspace availability on productivity (Hewage & Porwal, 2011)

Argument	Value
5	0.65
10	0.68
15	0.70
20	0.76
25	0.80
30	0.93
35	0.95
40	0.97
45	0.98
50	0.99



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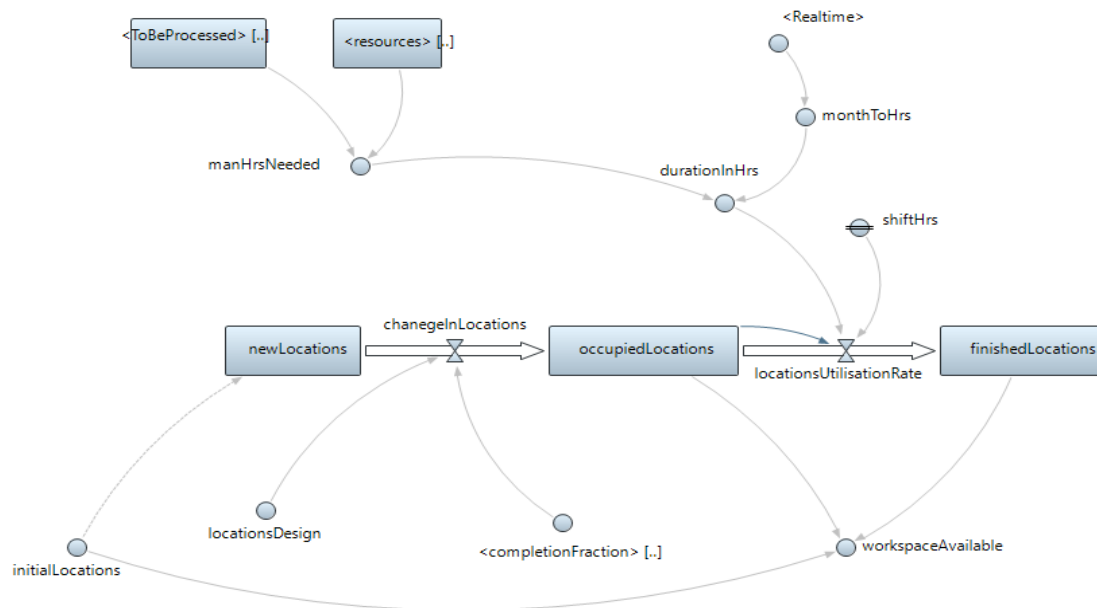


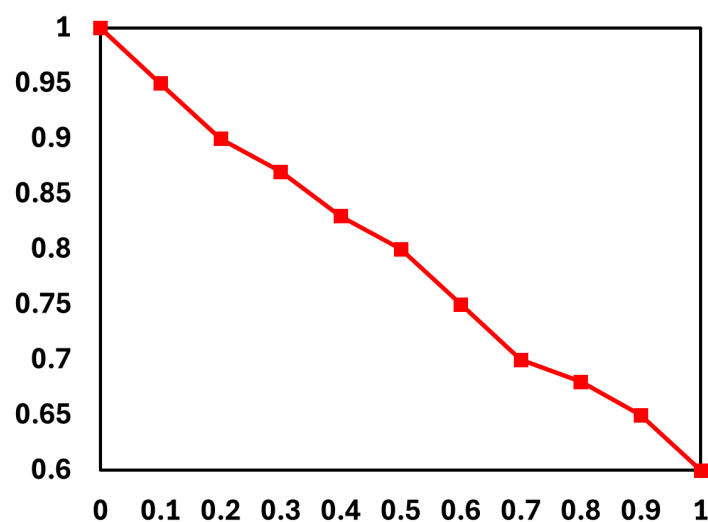
Figure 7-4 – Impact of workspace limitation on productivity.

- Effect of Fatigue on Productivity

Workers' productivity is influenced by the duration of daily task assignments, with scholarly research noting that the 'effect of fatigue' varies based on the ratio of average overtime allocated. As illustrated in Table 7-3, an increase in the Fatigue coefficient demonstrates a decline in productivity as the overtime ratio escalates, culminating in a maximum ratio of 1.0, wherein productivity decreases by 0.6 (García, 2020).

Table 7-4 - Lookup function of the impact of fatigue on productivity (García, 2020)

Argument	Value
0	1
0.1	0.95
0.2	0.9
0.3	0.87
0.4	0.83
0.5	0.8
0.6	0.75
0.7	0.7
0.8	0.68



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0.9	0.65
1.0	0.6

- The impact of schedule pressure and overtime policy

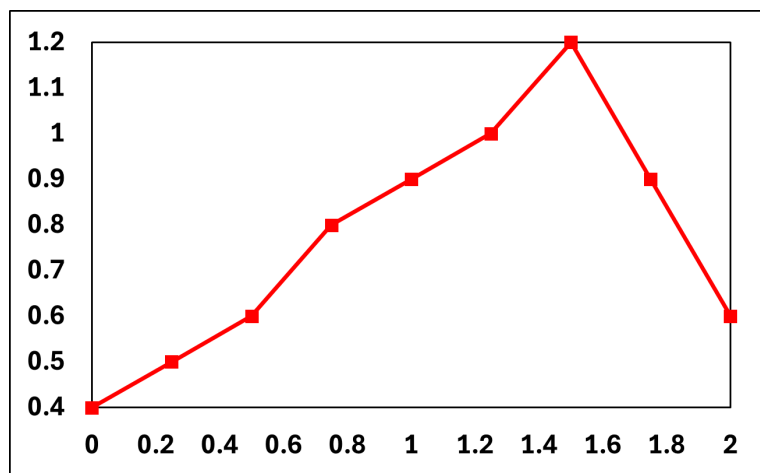
Ensuring the completion of construction activities is the best scenario for every project manager. However, schedule pressures indirectly influence productivity, compelling construction managers to implement policies such as increasing resources or adding overtime. The direct correlation between schedule pressure and overtime is delineated within the table function in

Table 7-5. The schedule pressure is calculated using the formula presented in Equation 7.6, which utilises conditional logic (IF and THEN) to assess whether the project has delays, so schedule pressure will be assigned the maximum value of 2, rendering it dimensionless (Kaya & Dikmen, 2024).

$$\begin{aligned} &\text{remainingTime}[\text{SUBSTAGES}] \leq 0 \quad \& \\ &!(\text{projectIsDone}[\text{SUBSTAGES}] \neq 0) ? \\ &\text{maxSchedulePressure} : \quad \text{Equation 7.6} \\ &\text{zidz}(\text{requiredWorkflow}[\text{SUBSTAGES}], \\ &\text{normalWorkFlow}[\text{SUBSTAGES}]) \end{aligned}$$

Table 7-5 - Lookup function of schedule pressure effect (Kaya and Dikmen, 2024)

Argument	Value
0.0	0.4
0.25	0.5
0.5	0.6
0.75	0.8
1.0	0.9
1.25	1.0
1.5	1.2
1.75	0.9



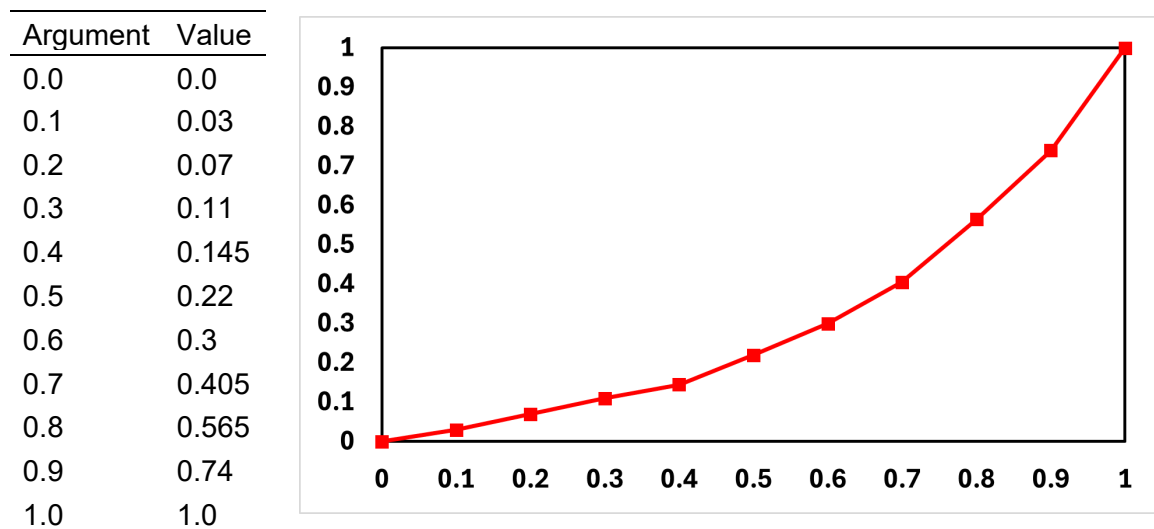
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2.0 0.6

- The impact of implementing BIM on productivity

This dynamic variable signifies the positive impact of BIM on productivity, as delineated by (Porwal, 2013) in Table 7-6. The values of the table function range from 0 to 1, with increments of 0.1. These values are dimensionless and reflect an exponential positive impact on productivity as BIM implementation increases; dimensionless—the specific variables about BIM's impact on productivity, denoted by BIMImpactOnProductivity.

Table 7-6 – Lookup function for the impact of applying the BIM process (Porwal, 2013).



7.4.4. Resources Subsystem

A trade analysis approach is employed, leveraging observed resources from case studies to estimate the number of tradespeople and engineers required to complete construction tasks. Subsequently, the current cost per labour hour can be calculated, providing insight into the workforce's productivity, expressed as the hours required for monthly output. The workflow needed in Equation 7.7 is contingent upon conditional logic (IF and THEN), which diagnoses whether the project is completed and if any

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Work-in-Progress (WIP) remains. In such cases, the maxflow is assigned the value of the required flow, with the maximum workflow “maxWorkflow” values set from SS1 to SS11 {185, 50, 100, 700, 104, 200, 50, 70, 1435, 215, 233} denominated in “Tasks” unit. If the diagnosed condition is not met, the requiredWorkflow takes the maximum value between ToBePrecessed divided by remainingTime. The xidz function is employed to avoid division by zero, returning the maxWorkflow value if division by zero occurs to prevent not a number (NaN) value.

The dynamic variable resourceGap regulates the required resources over time if the condition in Equation 7.9 is satisfied. Additionally, this dynamic function determines the number of trades to be dismissed after passing “half month,” as assumed in the model. The dynamic variable Tot_Reosources aggregates the values between the new workforce hired and the resources working on assigned tasks in the project. The change resources in Equation 7.10 divide the value of newWorkForce by the user-input value resourceAdjustmentTime, which is assumed to be “2 months”.

$$\begin{aligned} \text{projectIsDone}[\text{SUBSTAGES}] & \neq 0 \ \&\& \ \text{WIP}[\text{SUBSTAGES}] < 0 ? 0 : \\ \max(\text{xidz}(\text{WIP}[\text{SUBSTAGES}]), & \text{remainingTime}[\text{SUBSTAGES}], \text{Equation 7.7} \\ \text{maxWorkflow}[\text{SUBSTAGES}] &), \text{maxWorkflow}[\text{SUBSTAGES}]) \end{aligned}$$

$$\min(\text{maxResources}[\text{RESOURCES}], \text{RR}[\text{RESOURCES}] / \text{normalProductivity}) \quad \text{Equation 7.8}$$

$$\begin{aligned} \text{resourceGap} = & \\ \text{TOT_Resources}[\text{RESOURCES}] & < \text{requiredResources}[\text{RESOURCES}]? \\ (\text{resourceAllocation}[\text{RESOURCES}] & * \text{requiredResources}[\text{RESOURCES}]) \quad \text{Equation 7.9} \\ + ((1 - \text{resourceAllocation}[\text{RESOURCES}]) & \\ * \text{TOT_Resources}[\text{RESOURCES}]) & : \text{requiredResources}[\text{RESOURCES}] \end{aligned}$$

$$\begin{aligned} \text{changeInResources} & \\ \text{newWorkForce}[\text{RESOURCES}] / \text{resourceAdjustmentTime} & = \quad \text{Equation 7.10} \end{aligned}$$

$$\begin{aligned} \text{TOT_Resources}[\text{RESOURCES}] & < \text{requiredResources}[\text{RESOURCES}]? \\ (\text{resourceAllocation}[\text{RESOURCES}] & * \text{requiredResources}[\text{RESOURCES}]) \quad \text{Equation 7.11} \\ + ((1 - \text{resourceAllocation}[\text{RESOURCES}]) & * \text{TOT_Resources}[\text{RESOURCES}]) \\ : \text{requiredResources}[\text{RESOURCES}] & \end{aligned}$$

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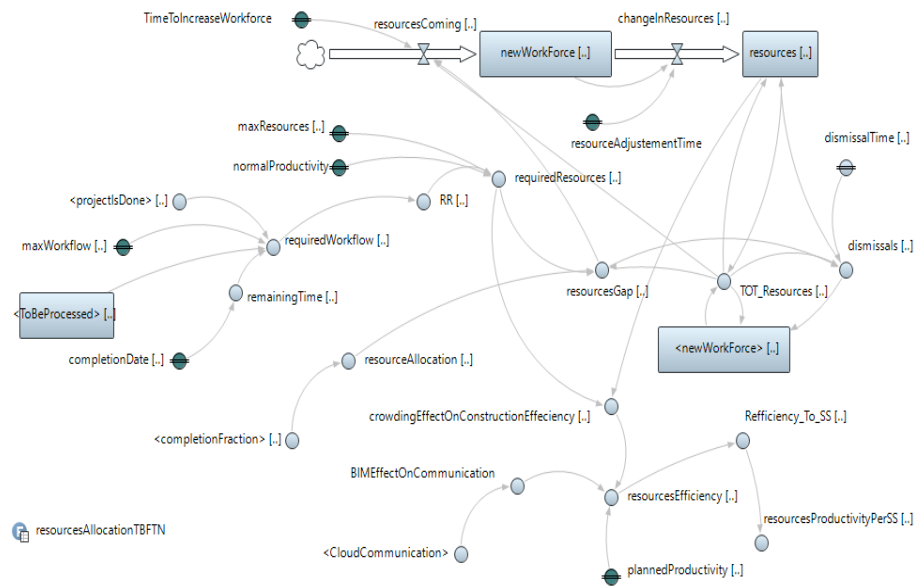
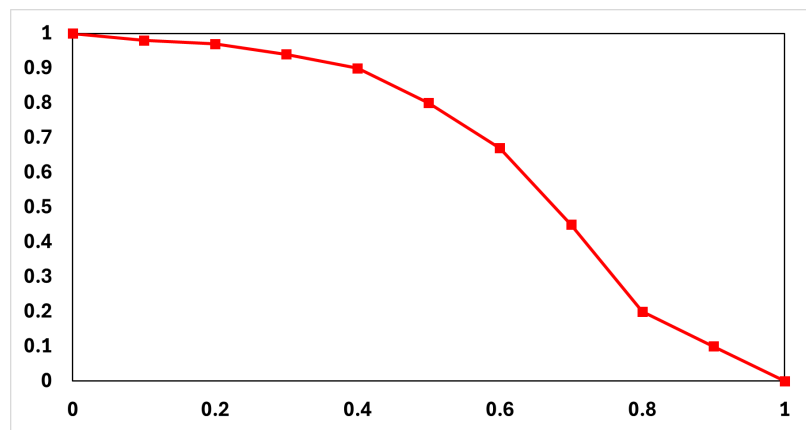


Figure 7-5 – The dynamic subsystem for Resources.

Table 7-7 represents a table function that is used to determine the percentage of labour needed at each stage of the project; this lookup function returns the percentage of each RESOURCES needed (T1-T11) according to the percentage of workprogress (Lyneis et al., 2001).

Table 7-7 – Table function of resources allocation needed following the fraction of project completed.

Argument	Value
0.0	1.00
0.1	0.98
0.2	0.97
0.3	0.94
0.4	0.90
0.5	0.80
0.6	0.67
0.7	0.45
0.8	0.20
0.9	0.10
1.0	0.00



7.4. Dynamic Interplay among LPS and BIM for MD Mitigation

This section details the dynamic relationship between LPS and BIM and their influence on MD mitigation and propagation. That can be broken down into the social LPS subsystem, technical LPS subsystem, and BIM functionalities subsystem.

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7.4.1. The dynamic relationships among the social factors in the LPS

In Figure 7-6, the LPS subsystem encompasses three dynamic variables: collaboration (COO), making do knowledge (MDK), and LPS technical functions (LPSF_S). Within the COO_F flow, four distinct parameters are VA1, VA2, VA3, and VA4, interlinked with the overarching concept of cooperation. The *MDK* variable, in turn, is contingent upon the level of coaching and training, data bank generation, knowledge transferred between projects, and transforming knowledge from experience. Moreover, the BIM subsystem indirectly reinforces learning because the ease of understanding BIM outputs can increase situational awareness in the construction teams (Sacks, Korb, et al., 2018). Notably, a relationship exists between data bank generation and attributes within the visualisation dynamic variable in the BIM subsystem. According to the SEM in Chapter 5, the relationship between BIM and MDK is insignificant, and the LPS mediate this relationship, similarly to COO.

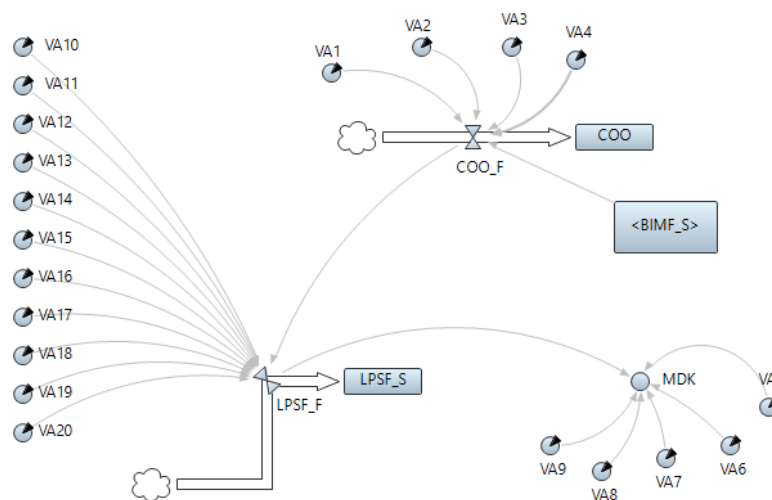


Figure 7-6: The LPS dynamic subsystem

7.4.2. The dynamic relationships among the technical factors in the LPS

In Figure 7-7, the technical subsystem of the LPS relies on three dynamic variables: *VisualManagement*, *LookAheadPlanning*, *ShortTermPlanning*, and *ProductionPlanMetrics*. The *VisualManagement* dynamic variable includes interdependent parameters such as *BIMmodelAvailableDuringSession*, *KeepAllPlansPublic*, and *UsingGuidingMDInformationBrochures*. It directly depends on the functionalities of BIM, utilising its three functionalities to represent essential information on products, tasks, quantities, start and end times, clashes, and interdependencies.

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LookAheadPlanning, considered pivotal in LPS implementation (Ballard & Tommelein, 2021; Hamzeh & Aridi, 2013), involves breaking down processes from Critical Path Method (CPM)-based schedules into actionable operations and work packages. It is collaborative in diagnosing production constraints and allocating necessary resources. The *LookAheadPlanning* dynamic variable comprises four interdependent parameters: *constraintsAnalysisAndRemoval*, *TaskBreakDown*, *CollaborativeDesignofOperations*, and *MaintainingWorkableBacklog*. These parameters interact with both the LPS social subsystem and BIM functions, influencing the reliability and success of Lookahead Planning.

The *ShortTermPlanning* dynamic variable focuses on streamlining daily huddles (*DailyHuddles* parameter) and frequent discussions of constraints (*dailyDiscussionOfConstraints*). The dynamic parameter collectively evaluates these *ProductionPlanMetric* variables, defining the accuracy of the Percent Plan Complete (PPC) measure in the LPS. The reliability of LPS in Planning and Control is contingent on the quality of information delivered to the system. Missing or incorrect PPC input complicates the tracking of LPS reliability in Planning and Control processes when incorrect feedback about constraint removal and informal processing for constraints exists that leads directly to MD behaviour, which distorts the PPC measurement (Formoso et al., 2017; Viana et al., 2017).

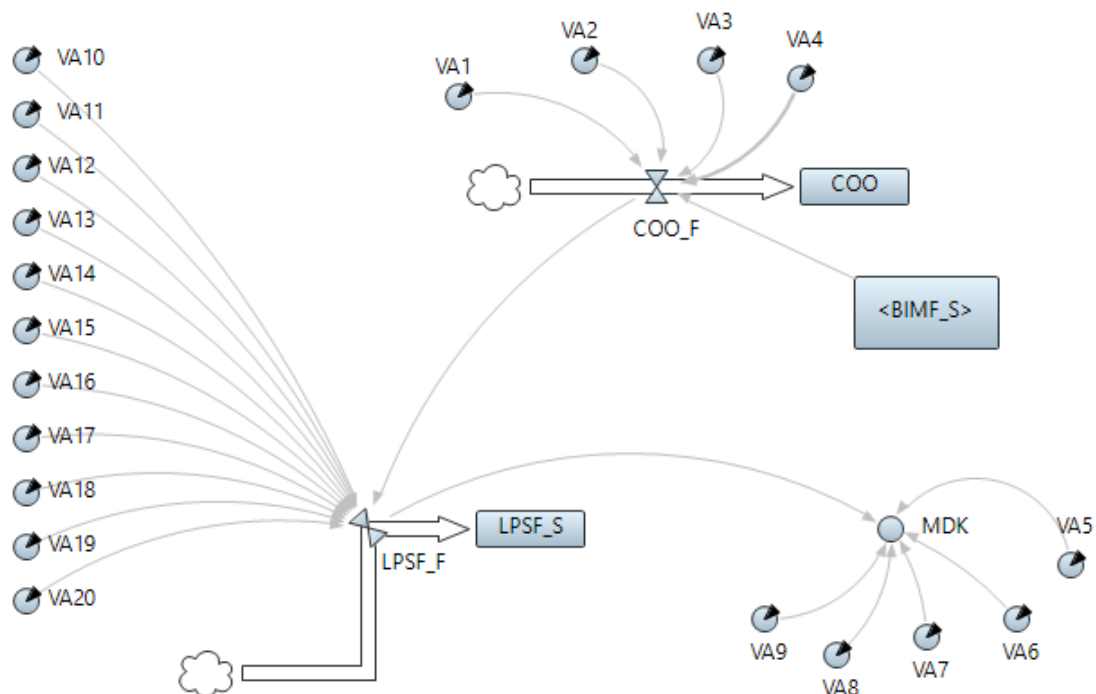


Figure 7-7 - The technical LPS dynamic subsystem

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7.4.3. The dynamic relationships in BIM functionalities

The BIM functionalities are proposed here as an integrative information technology to model and manage the construction information and provide advanced analysis and fine-tuned representation to aid the construction practitioners in delivering their functions properly with less information fragmentation, interruption, and redundancy. In this simulation, we test four functionalities of BIM (4D planning, "Phase planning," visualisation, clash detection, and cloud communication). These functionalities also have dynamic relationships, such as the relationship from 4D planning and clash detection to visualisation. Interdependencies with LPS technical and social subsystems were also drawn. For example, visualisation functionality has a direct relationship with keeping plans public (Keep All Plans Public), and 4D planning impacts the availability of plans in public (BIM Model Available During LPS Session) and increases the level of coordination in the social LPS subsystem (COO). A collective dynamic variable called BIMfunctions may also positively impact the collaborative design for operations.

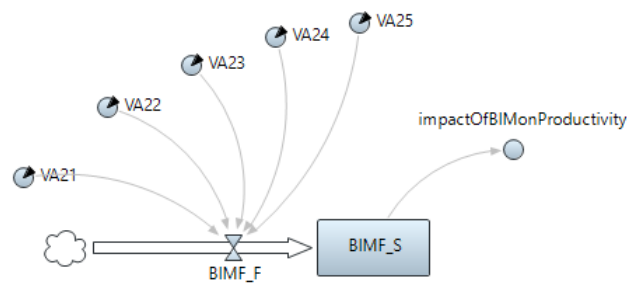
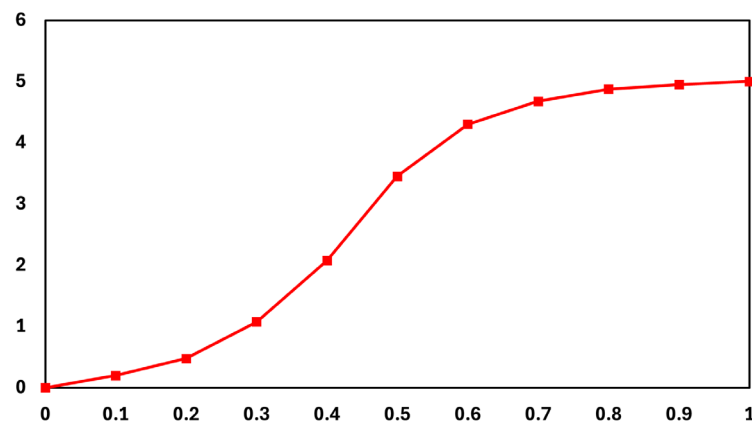


Figure 7-8 – BIM functionalities subsystem

Table 7-8 – Lookup the commitment function to implement BIM processes (Porwal, 2013).

Argument	Value
0.0	0
0.1	0.2
0.2	0.475
0.3	1.075
0.4	2.075
0.5	3.45
0.6	4.3
0.7	4.675



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0.8	4.875
0.9	4.95
1.0	5.0

7.5. Simulation and Impact Measurement

This section runs a dynamic simulation to investigate the impact of LPS and BIM on MD by utilizing input data for Project A for sixty months and B for forty months. The models for Project A and B ran successfully. The units used to measure the variables in this model were tested for their consistency, and then the stability of the model for extreme conditions was applied. Parameter variation testing was applied to analyse four combinations of LPS and BIM uses. The results of this section quantify the accumulation of MD, constraints, and waste over time for the studied scenarios using comparative analysis for the effectiveness of the strategies of LPS-BIM.

7.5.1. Explanation of the Simulation Methodology

The simulation process encompassed the establishment of assumptions to set the boundary conditions for the model, outlined in Table 7-9 and Table 7-10. These assumptions guided the inputs for baseline simulation for Projects A and B. Random numbers were systematically generated for resource productivity timing employing the `uniform_discr` function to simulate real-world variability, creating a discrete distribution between 20 and 40. Throughout the iterative model development phase, actual project data served as the foundation for these values, ensuring the reliability of the simulated results. Upon validation against the baseline scenario, the final Stock and Flow Diagrams (SFDs) were calibrated for subsequent scenario testing. A comparison between the baseline simulation results and empirically collected data is presented in Table 7-11, validating the model's predictive accuracy and real-world applicability.

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Table 7-9 – Data entered in AnyLogic for critical variables of the baseline scenario (Projects A and B)

Project	Subsystem	Parameter	Input	Units
Project M	Work	Floor Area	6,323	Square meter
	Progress	Project Duration	60	Month
		Max Workflow {SS1-S11}	{124,34,67,469,70,135,34,47,962,144,157}	Task / Month
		Planned		
	Resource	Completion Months {SS1-SS11}	{34,34,34,28,21,23,27,37,34,21,34}	Month
		Max Resources {R1-R12}	{33,67,54,54,47,67,67,134,33,67,54,134}	Person
Project B	Work	Floor Area	2,912	Square meter
	Progress	Project Duration	40	Month
		Max Workflow {SS1-S11}	{56,15,30,212,31,61,15,21,435,65,71}	Task / Month
		Planned		
	Resource	Completion Months {SS1-SS11}	{16,16,16,13,10,11,13,17,16,10,16}	Month
		Max Resources {R1-R12}	{33,67,54,54,47,67,67,134,33,67,54,134}	Person

Table 7-10 – Input Data of the baseline scenario

Project	Subsystem	Parameter	Input	Units
Projects A, B	Cost	Overtime unit cost	1.2	\$/ Month
	Cost	Construction resource cost percentage	7.5	1/ (Person * Month)
	Cost	Indirect Cost Percentage	0.5	\$/Task
	Cost	Uncompensated Delay Cost	1.25	\$
	Location	Initial Location	50	Space
	Location	Location Design Rate	1	Space/ Month
	Resources	Dismissal Time	0.5	Month

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Resources	Resource Adjustment Time	2	Month
Resources	Normal Productivity	4	Task/ (Month * Person)
Resources	Planned Productivity	uniform_discr(20,40)	Task/ (Month * Person)
Overtime	Time to average overtime	2	Month
Overtime	Max Schedule Pressure	2	unitless

Table 7-11 – Comparison of system dynamic model with project data

Category	Additional Cost (\$)	Actual Completion Rate (%)	Total MD (Tasks)	Constraints (Tasks)	Waste (Tasks)
Baseline A	80,479.86	93.754	196.163	1454	3,295
Project A data	78,690	94	211	1300	3,590
Baseline B	28,624.77	98.338	182.637	868	2,065
Project B data	30,000	99	183	850	2,200

7.5.2. Testing for Model Units Consistency

As one of the critical validation steps for computerized modelling, a dimensional consistency test was conducted on Anylogic's unit checker. Initially, when transferring conceptual models to stock flows, it was noted that the model had over 150 warnings, which were promptly rectified to achieve coherence.

7.5.3. Model Stability Testing

The stability test is conducted to securitise the evolution trend of the curve in different subsystems and the stability of the fitting under different time-step settings. The subsystems' work progress, locations, cost, productivity, and resources are tested. The test examined the stability of crucial systems by employing three distinct step sizes: 1/100, 1/50, and 1 month. The MD, constraints, and waste stocks at different steps are highly consistent, indicating that the system is stable and reliable.

7.5.4. Parameter Variation Testing

The parameter variation test investigates the influence of the dynamic behaviour in the long run, which determines the optimal parameter values for the studied system; it is also used to simulate external behaviour dynamics and the dependence structure analysed in plots for studied variables (Lakshmikantham & Deo, 2019). This test, delineated in Table 7-12, shows the assumptions used for

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parameter variation tests, comprising four scenarios testing. This parameter variation testing verifies (1) the impact of LPS technical factor at the maximum value in Scenario I, (2) the impact of collaboration is associated with LPS technical factors by enabling VA6, VA7, VA8, and VA9, (3) LPS socio-technical factors with the association of MDK and (4) all parameters of the study LPSF, BIMF, COO, and MDK. This testing procedure validated the model's efficacy in simulating real-world dynamics and elucidating complex system behaviour.

Table 7-12. The mix of variables to be tested in Scenarios I to IV.

	Tested variable	Involved parameters	Values
Scenario I	LPS technical factors enabled	VA10, VA11, VA12, VA13, VA14, VA15, VA16, VA17, VA18, VA19, VA20, VA21	All values set to five
Scenario II	LPS technical factors enabled, associated with collaboration factors	VA6, VA7, VA8, VA9, VA10, VA11, VA12, VA13, VA14, VA15, VA16, VA17, VA18, VA19, VA20, VA21	All values set to five
Scenario III	LPS socio-technical factors enabled with the association of Making-Do Knowledge factors	VA1, VA2, VA3, VA5, VA6, VA7, VA8, VA9, VA10, VA11, VA12, VA13, VA14, VA15, VA16, VA17, VA18, VA19, VA20, VA21	All values set to five
Scenario IV	LPS socio-technical factors + BIM enabled	VA1, VA2, VA3, VA5, VA6, VA7, VA8, VA9, VA10, VA11, VA12, VA13, VA14, VA15, VA16, VA17, VA18, VA19, VA20, VA21, VA22, VA23, VA24, VA25	All values set to five

7.5.5. Time series analysis for accumulation of MD, constraints, and waste

Examining temporal sequence data is a crucial aspect of the impacts generated by system dynamic simulations. Through time series simulation, a straightforward comparison emerges between the actions of a fundamental process and the results obtained from implementing policies and strategies; even for individuals lacking expertise in system dynamics modelling, it would be a straightforward representation of the studied system's systematic behaviour.

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Figure 7-9 illustrates the impact of functionalities like technical LPS, socio-technical LPS, and BIM on analysing constraints to enhance production plan performance by removing constraints from the planned activities. Notably, the baseline simulation has the least rigorous constraints inspection protocol and displayed the greatest number of tasks that proceeded without resolving constraints, as the count of identified constraints steadily rose from 0 to 27th months with a maximum value of 2183.747 constraints found. Regardless of the approach, Baseline Scenario I or II, the least constraints found at the end of the simulation were the least because the uncertainty about constraints reduces as the work proceeds. In the scenario I, around 22.114% of constraints were resolved after 27 months, with a clear reduction from the baseline emerging from the eleventh month onwards. Furthermore, the monthly graph depicts a marked decrease in newly identified constraints from months 27 through 60. The collaborative parameters assumed a pivotal role post the 20-month mark with the introduction of the MDK, leading to significant outcomes by resolving at least 547 for Scenario II and 888 for Scenario III constraints within the initial fourteen months of the project.

Interestingly, simulations under Scenario IV indicate that stakeholders are more prone to identifying early constraints when utilising LPS and BIM countermeasures. Integrating social and technical LPS concerns with BIM functionalities simplifies the early anticipation of all the project constraints after 13 months. Scenarios I, II, III, and IV yielded comparable results within the project. In contrast, the baseline simulation overlooked the delay in resolving 155 constraints after the simulation finished, concluding without any remaining constraints, which, under traditional production planning and control methods, could result in added expenses and delays due to uncertainties associated with these constraints.

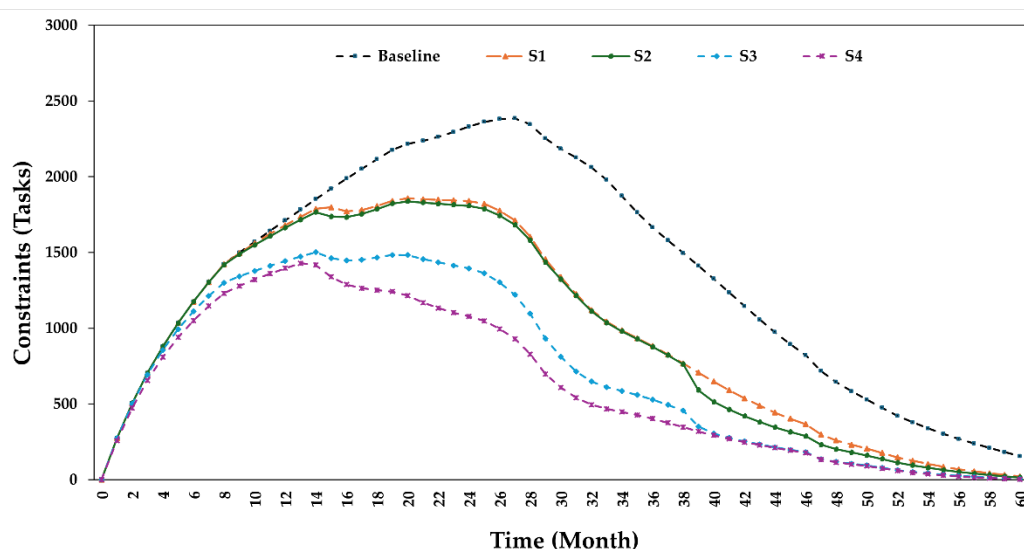


Figure 7-9 - Time analysis for constraints in Project A

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Figure 7-10 illustrates the cumulative incidence rate of MD categories over 60 months in project A under the baseline scenario vs scenarios I, II, III, and IV. One of the primary challenges encountered pertains to the persistent delay, spanning two months, in addressing MD, attributed to the prioritization of technical aspects within the framework of the Last Planner System. It is worth noting that a comprehensive solution cannot be achieved without addressing the social dimensions of the issue. These socio-technical elements, deemed critical for fostering collaborative and integrated production planning and control, could offer valuable insights into the root causes of MD incidents or even allow for anticipating MD triggers, thereby enabling proactive mitigation measures. The analysis reveals a transition from an initially perceived advantage to a realisation of drawbacks in Scenarios I and II between the 6th and 24th months, as decisions made during this period inadvertently led to the generation of waste, which in turn had adverse consequences. Ultimately, Scenario III emerged as the preferred course of action, succeeding in halving the occurrence of MD. Furthermore, Scenario IV positively impacted mitigating MD instances, demonstrating a comparable reduction to Scenario III.

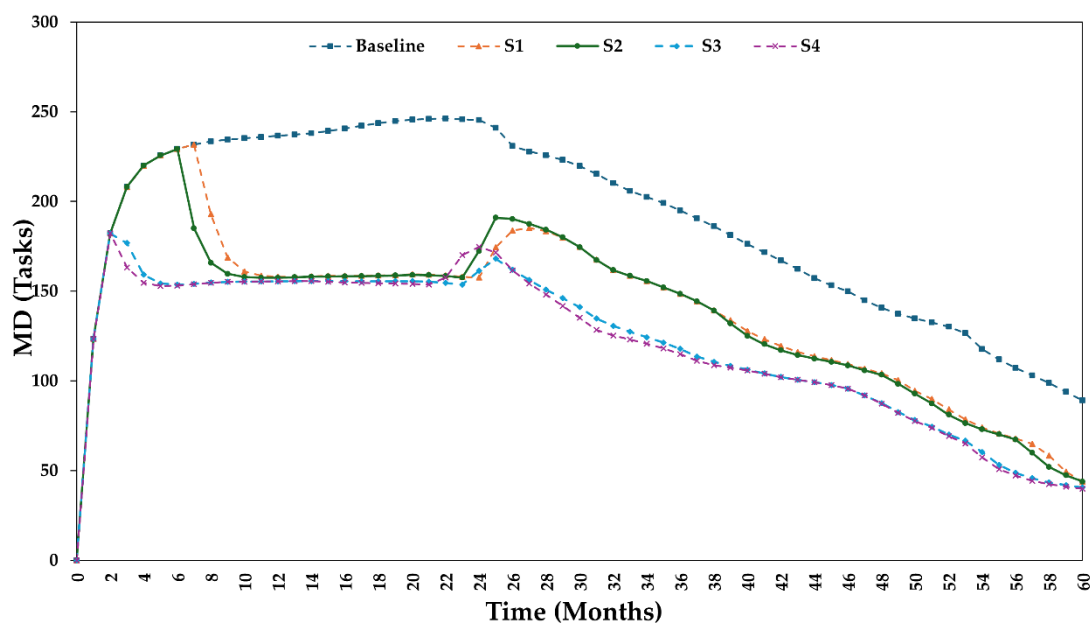


Figure 7-10 – Time analysis for MD in Project A

Figure 7-11 elucidates the escalation of waste levels across 52 months across all potential scenarios. It demonstrates the gradual process of waste accumulation, followed by a subsequent reduction, encompassing nearly half of the entire duration. This inference sheds light on the futility of a reactive approach to waste reduction. Nevertheless, the outcomes of Scenarios I and II exhibit similarity in that waste is halved compared to the initial levels observed in Project A. Scenarios III and IV yielded the most pronounced outcomes, particularly Scenario MDK, which yielded even lower waste volumes. The

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dwindling trend in the time variable, depicted in Figure 7-10, can be ascribed to the heightened emphasis on diminishing the quantity of MDs.

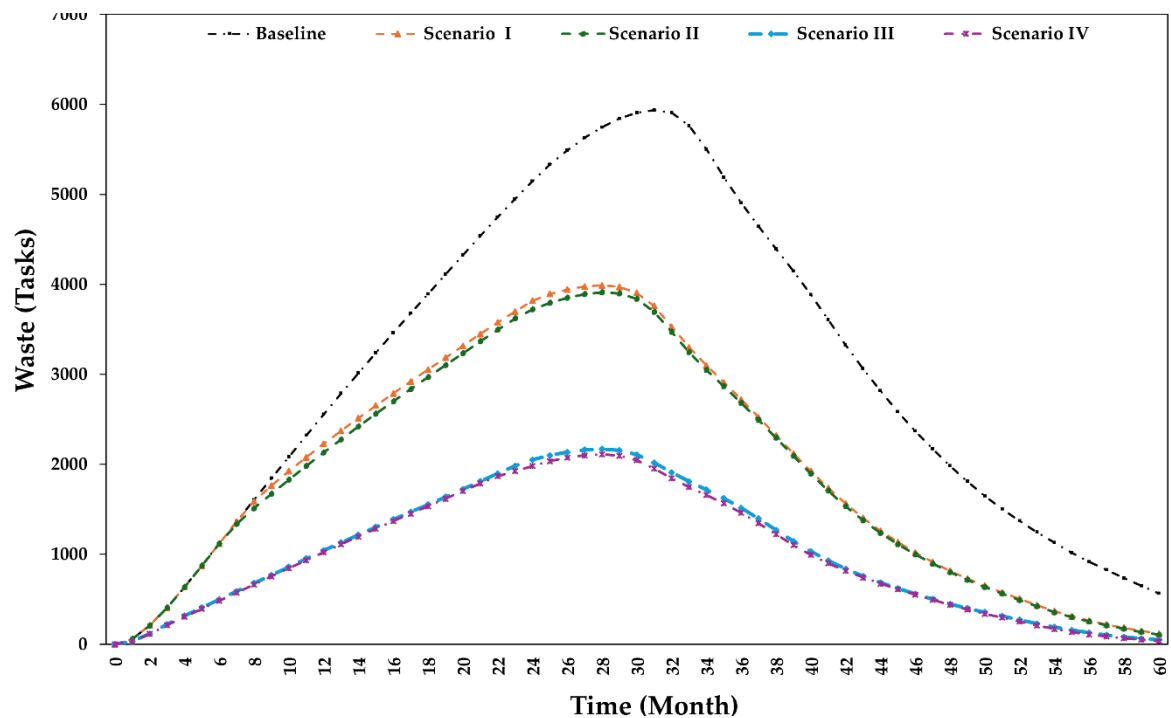


Figure 7-11 – Time series analysis for waste in Project A

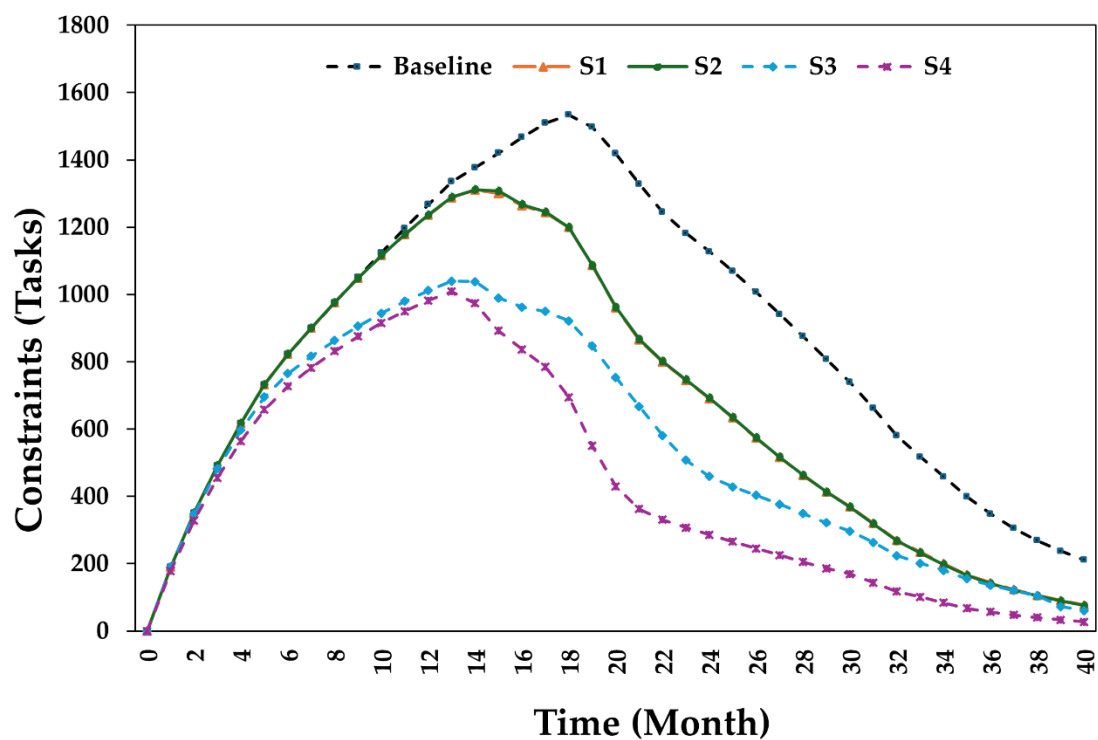


Figure 7-12 – Time analysis for constraints in Project B

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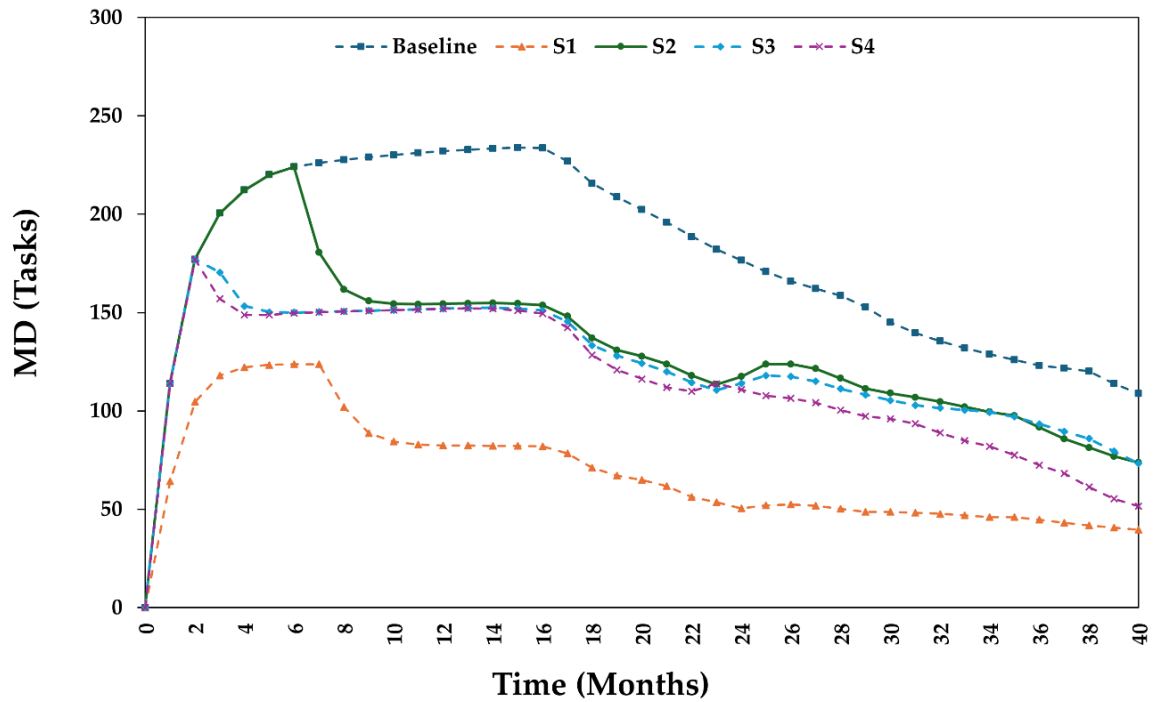


Figure 7-13 – Time series analysis for waste in Project B

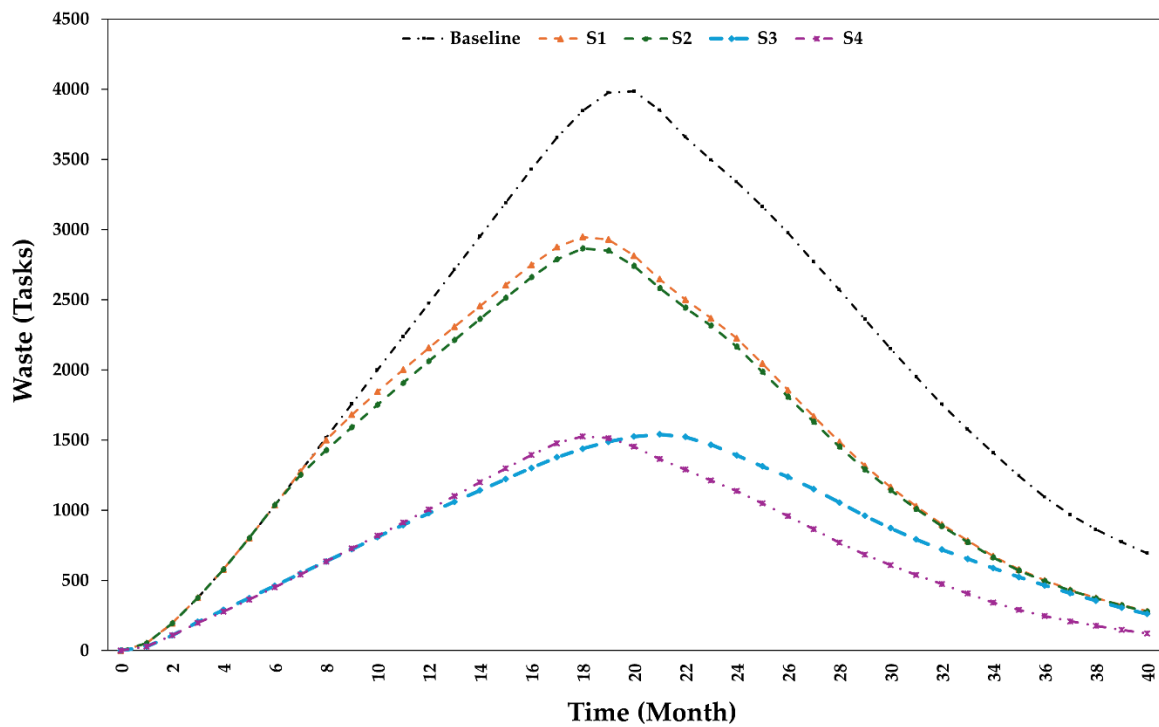


Figure 7-14 – Time analysis for waste in Project B

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7.5.6. Comparative Analysis for the effectiveness of the strategies of LPS-BIM on the average mitigation of MD, constraints, and waste

Figure 7-15 and Table 7-14 evaluate the mean outcomes of project constraints following simulations spanning 60 months for project A. Constraint P1 resulted in 35 unresolved tasks at the baseline level. MDK parameters did not induce any modifications on P1 and P2; thus, Scenario I brought about alterations solely through technical LPS parameters, resulting in 26.05% for P1, while Scenario II yielded 40.84% and Scenario IV resolved 45.72% of uncertain constraints. All scenarios exhibited minimal impact on reducing P2 constraints, ranging from 12.87% to 26.27%, mitigated P2 constraints after applying parameter Scenario I to Scenario IV. Scenario IV halved the constraints of P3 and P5 compared to the baseline simulation, while Scenarios I and II equally resolved up to 29.61% of P3 and P5 constraints, and Scenario IV removed up to 57.8% of total constraints. P4 constraints experienced a removal rate between 24.11% and 47.69% by applying Scenarios I to IV, respectively. P6 experienced the most significant impact from Scenario IV, where an average reduction of 65.13% of constraints associated with this category was observed after 60 months of simulation runs.

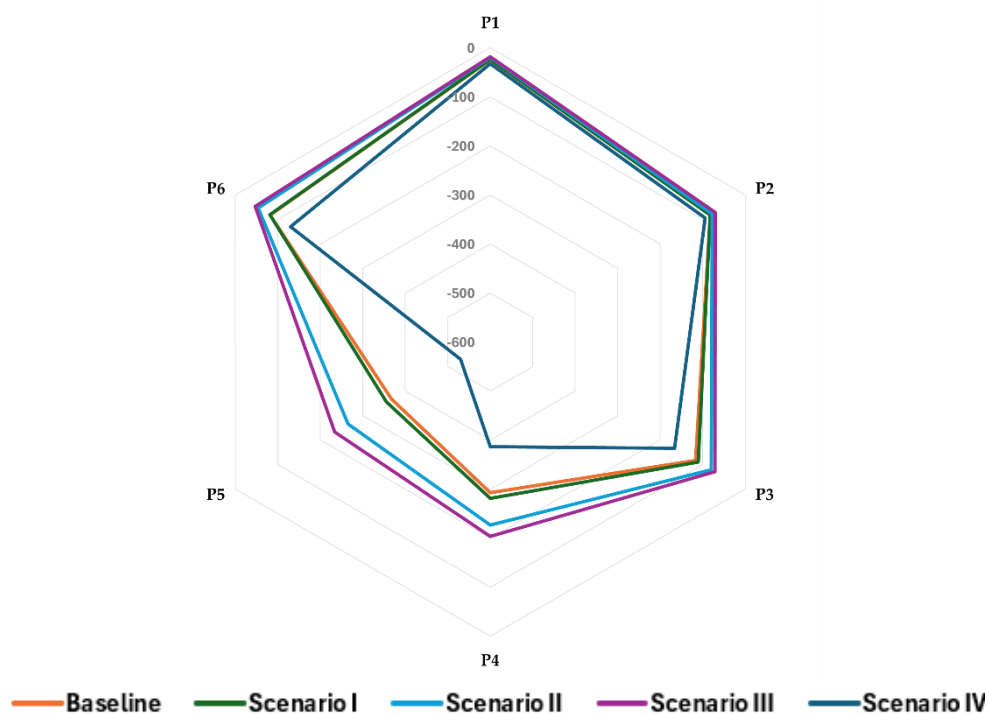


Figure 7-15 - Comparison between constraints P1 - P6 in project A

Table 7-13 – Constraints P1 to P6 in Project A Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
P1	33	24	24	20	18

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P2	94	83	82	78	71
P3	166	117	111	79	71
P4	386	293	281	227	203
P5	530	367	356	265	234
P6	130	82	81	54	47

Figure 7-16 and Table 7-15 compare the average outcomes of MD categories following a 60-month simulation period for Project M. Within Project A, CAT 2 also saw decreases in Scenario I by 24.62%, while in Scenario II, a quarter of MD CAT2 experienced reductions. Scenario III, on the other hand, showed minimal variance when compared to Scenario I and Scenario II, resulting in an overall decrease of 33.14. Nevertheless, the impact of BIM functionalities on MD CAT 2 was found to be negligible. This category holds significant importance among the various categories, surpassing all four categories regarding task infection, starting with a baseline of 99 tasks affected by CAT 2. The simulation of the baseline CAT 3 exhibited the fewest tasks compared to all other Categories. Scenario IV documented the highest mitigation rate, with 60.64% of all CAT3 tasks registered in the baseline simulation. This substantial percentage results from the limited number of CAT 3, impacting any assessment of the 60% decrease from scenario IV. The trend of CAT 4 mirrors the response of CAT 1 towards Scenarios I (16.84%), II (16.80%), III (24.90%) and IV (24.41%). Conversely, the mitigation rates of CAT 5 from the baseline to Scenarios I (27.75%), II (29.45%), III (44.71%) and IV (47.66%) differ.

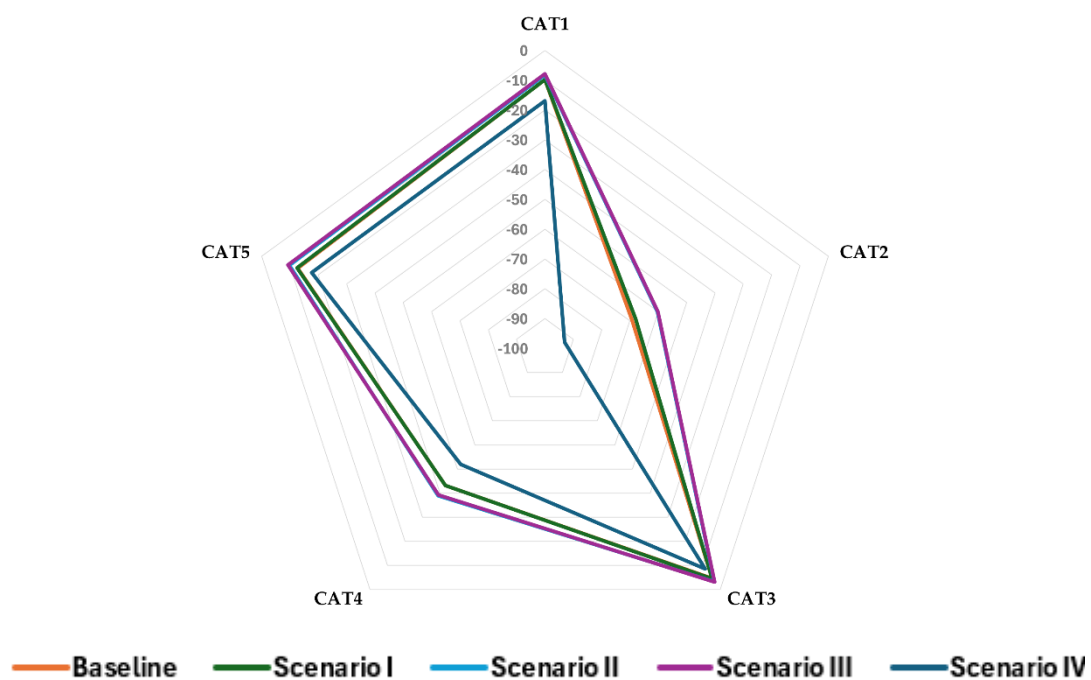


Figure 7-16– MD categories CAT1 to CAT5 comparison in project A

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Table 7-14– Making Do Categories CAT1 to CAT 5 in Project A Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
CAT1	17	10	10	8	8
CAT2	93	69	68	60	60
CAT3	9	5	5	3	3
CAT4	52	43	43	39	39
CAT5	18	13	12	10	9

Figure 7-17 and Table 7-16 present a comparative analysis of the mean outcomes concerning project waste post the execution of simulations spanning 52 months for project A. The simulations indicate a decrease in average waste ranging from 31.57% to 68.4% of the overall identified waste. The data illustrates that implementing LPS with BIM has proven effective in averting several managerial decisions before task commencement, reducing both process and physical waste. In terms of I1, applying LPS technical elements alone can enhance productivity by 31.57%, while incorporating MDK could elevate labourers' productivity efficiency by 66.77%. The simulations also reveal the capability of LPS socio-technical factors in mitigating approximately 59.83% of tasks that contribute to material waste (I2), directly correlating to a 68.55% reduction in reworks (I4) and indirectly through MD mitigation approaches. Moreover, the dynamic simulation data indicates that integrating LPS-BIM can diminish quality-related issues to below 70%, as documented in I3.

Table 7-15 – Waste I1 to I5 Project A Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
I1	254	167	162	75	70
I2	287	181	177	105	101
I3	325	212	207	104	102
I4	850	512	497	275	266
I5	1276	860	843	452	443

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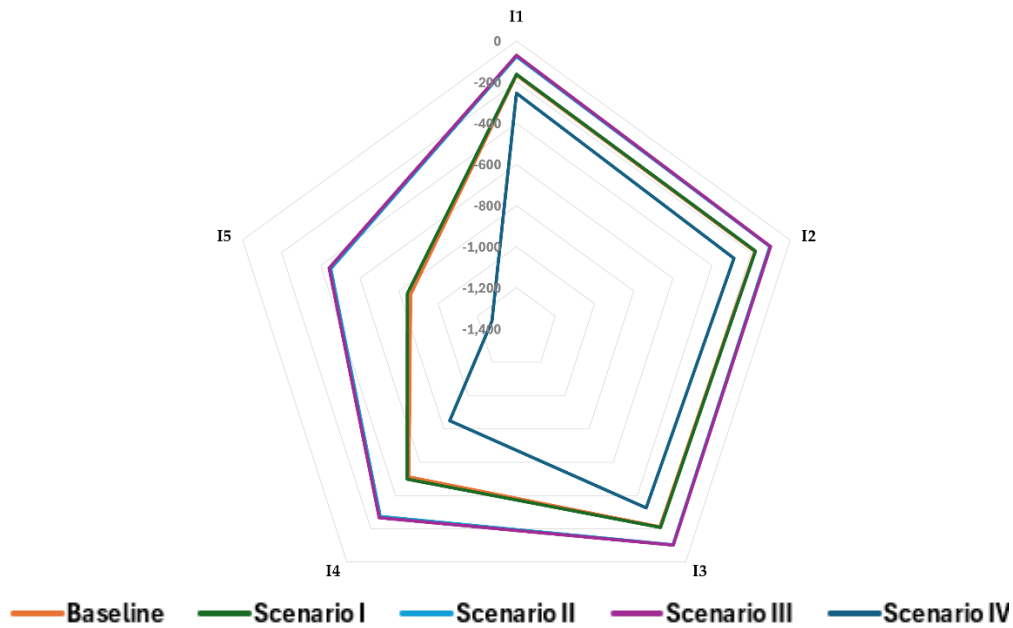


Figure 7-17 – Comparative analysis of the impact of MD I1-I5 in Project A

Figure 7-18 and Table 7-17 present the constraints observed in Project N across the baseline simulation and scenarios I, II, III, and IV. In Scenario I, P1 exhibits a reduction of 20.06%, followed by 20.03% in Scenario II, 31.59% in Scenario III, and 40.10% in Scenario IV. Meanwhile, P2 experiences comparatively lower reduction rates across the scenarios: 9.26% in Scenario I, 9.23% in Scenario II, 11.07% in Scenario III, and 18.89% in Scenario IV. The reductions for P3 range from 26.51% to 55.22%, while P4 sees reductions ranging from 21.27% to 43.75%. Similarly, P5's reduction rates vary from 25.95% to 52.93%. For P6, reductions are recorded at 30.27% in Scenario II, 30.28% in Scenario III, 49.79% in Scenario III, and 61.21% in Scenario IV.

Table 7-16 – Constraints P1 to P6 in Project B Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
P1	21	17	17	29	12
P2	61	55	55	118	49
P3	108	79	79	108	48
P4	243	192	192	331	137
P5	347	257	257	398	163
P6	89	62	62	89	34

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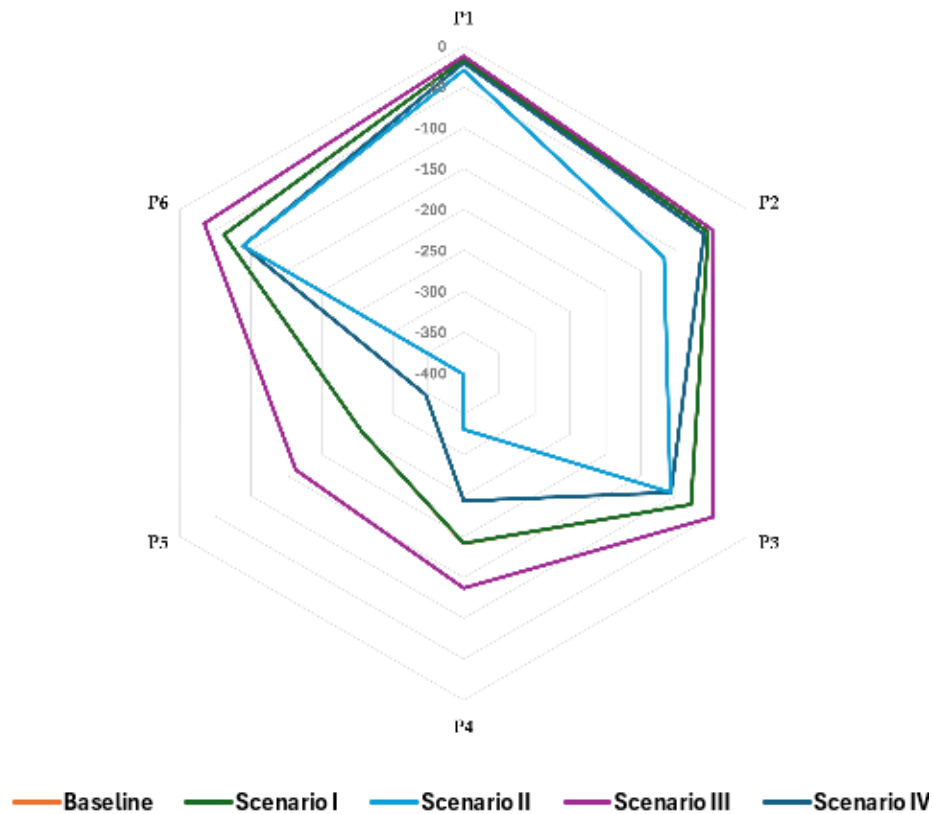


Figure 7-18 – Comparison between constraints P1 - P6 in project B

Figure 7-19 and Table 7-18 present the constraints observed in Project B across the baseline simulation and scenarios I, II, III, and IV. In Scenario I, P1 exhibits a reduction of 20.06%, followed by 20.03% in Scenario II, 31.59% in Scenario III, and 40.10% in Scenario IV. Meanwhile, P2 experiences comparatively lower reduction rates across the scenarios: 9.26% in Scenario I, 9.23% in Scenario II, 11.07% in Scenario III, and 18.89% in Scenario IV. The reductions for P3 range from 26.51% to 55.22%, while P4 sees reductions ranging from 21.27% to 43.75%. Similarly, P5's reduction rates vary from 25.95% to 52.93%. For P6, reductions are recorded at 30.27% in Scenario II, 30.28% in Scenario III, 49.79% in Scenario III, and 61.21% in Scenario IV.

Table 7-17 – Making Do Categories CAT1 to CAT 5 in Project N Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
CAT1	15	10	9	8	8
CAT2	90	68	67	61	60
CAT3	6	3	3	2	2
CAT4	51	41	41	37	37
CAT5	16	11	10	8	8

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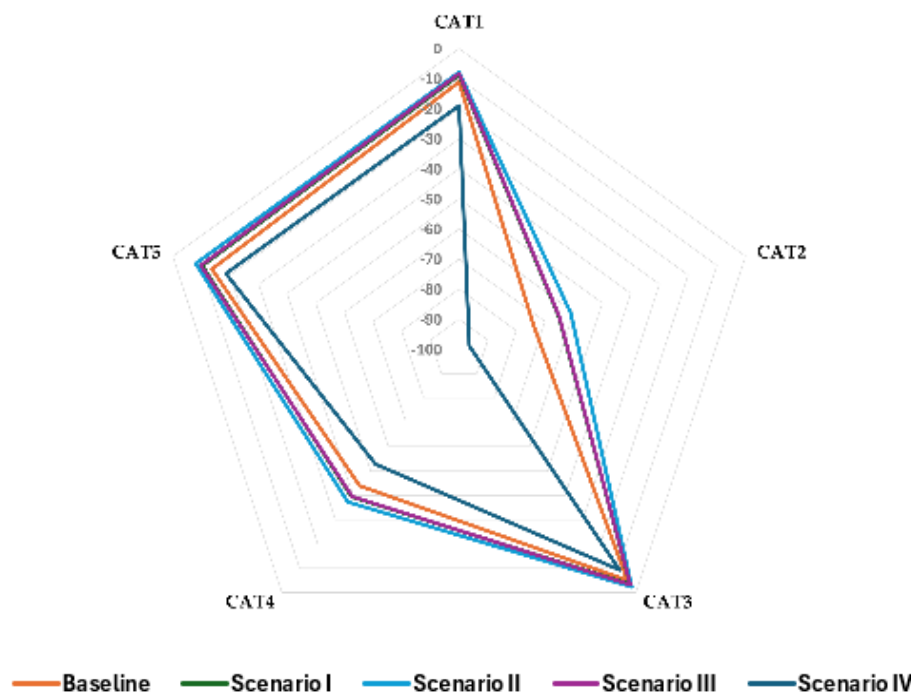


Figure 7-19 – MD categories CAT1 to CAT5 comparison in project B

Table 7-19 and Figure 7-20 describe a detailed contrast of the extent of changes that MD impacts I1 – I5 under scenarios I – IV of Project B, but it is empirically confirmed in all cases that big drops can be expected, moreover the highest ones by IV scenarios. In this case, baseline data of the conditions that display 164 tasks for category I1 drops by 33.43% when Scenario I is applied. All scenarios have marked reductions with increasing rates when moving from Scenario I, Scenario II, and Scenario III to Scenario IV, where Scenario I has the lowest impact and Scenario IV has the highest waste elimination rate. The category of waste I1 registered 164 tasks at the baseline simulation, Scenario I (33.43%), Scenario II (35.83%), Scenario III (65.95%), and Scenario IV 72.95 with 44 only tasks experienced category I. Similarly, it is clear to see the same response in MD impacts I2, I3, I4, and I5 when the mentioned scenarios are simulated.

Table 7-18 – Waste I1 to I5 Project B Simulation

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
I1	164	109	105	48	44
I2	171	123	119	70	66
I3	215	158	153	78	76
I4	656	458	444	241	231
I5	860	624	608	322	312

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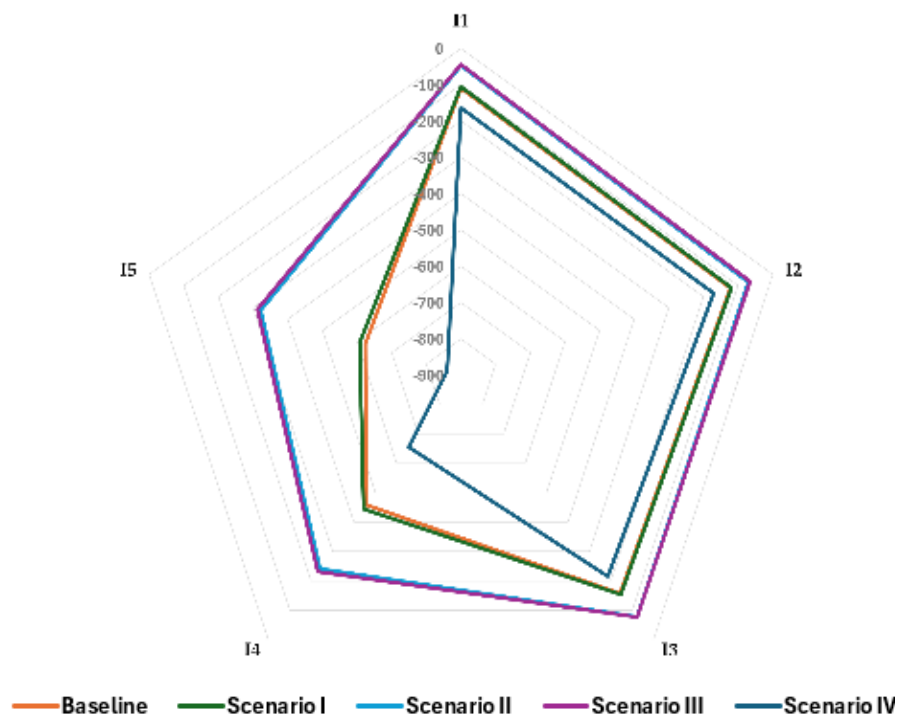


Figure 7-20 – Comparative analysis of the impact of MD I1-I5 in Project B

7.6. Discussion

MD could be evaluated by simulating two projects using Anylogic software, 5 MD categories, and six constraints. The baseline simulation for these values was accurate with over 90% precision in estimating five categories of MD, six constraints, five types of construction waste, additional cost incurred by MD, and completion fraction. This precision in simulating the baseline enabled further runs to evaluate four different scenarios of LPS-BIM combination. A total of 15 runs were applied using extreme value conditions, assuming the highest scale (five) for all LPS parameters for Scenario I, setting five scales for all COO parameters to simulate Scenario II, MDK parameters for Scenario III, and BIM for Scenario IV. MD categories, constraints, and waste values have been reduced in each scenario. This reduction shows that the LPS-BIM policy is valid for mitigating MD decisions, improving constraints analysis functions, reducing construction wastes, and improving labour productivity, resulting in cost reduction and delays.

Thus, LPS can reduce errors caused by working under high pressure and fatigue due to overtime and indirectly mitigate environmental impacts. In the developed simulation model, by setting up pull-driven process management, task deadlines can be adjusted depending on actual demand after each

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weekly work plan cycle (Nguyen & Sharmak, 2022). Some construction disruptions are related to the project team's inadequate perception of the project status, including their work and others' (Ma & Sacks, 2016). This disruption resulted in missing milestones and derailed projects. By contrast, Daily Huddle can connect project teams to synchronise information flow and verify that work progresses as the project continues.

The applied simulation can potentially support the project teams in improving construction plans and eliminating waste in their projects. By using cloud or software, planners can assess their production with MD characteristics and then quickly assess all required data to perform. D3M can be easily applied to assess other types of construction, including larger or smaller construction projects. For other construction types, personalised project parameters include floor area, planned start and finish dates, the stages and substages included in the project, the number of maximum human resources, and the number of locations. Creating the necessary parameters requires reevaluating the underlying regression equations within the D3M. Regarding other types of construction projects, such as healthcare projects and industrial buildings, re-evaluation for the kinds of stages and substages is required. As for all building types, it appropriately characterises the master schedule and resources.

However, there are some drawbacks to this model. It is possible to highlight the knowledge requirements for using system dynamic models and multiple data collection methods for better accuracy of mathematical modelling. This task can be labour and cost-intensive since automatic data capturing for MD variables was not used. Additionally, the probability of connection between Excel spreadsheets and Anylogic could be an issue when the file and rows and columns within the Excel file are not named as programmed in the system dynamic model, which requires double-checking the spreadsheet format and naming before running the model. An automated way to extract, adapt, and link spreadsheets and D3M is needed to use Anylogic extensively for MD analysis.

7.7. Conclusion

This chapter diagnoses the strategies of LPS and BIM to limit the MD phenomenon. That required to expand the proposed SDM in Chapter 6 to include variables such as human resources, productivity, locations, and cost related to MD decisions. Then, it incorporates them with the key dynamic factors that constitute LPS and BIM strategies. Finally, it simulates the situation using the case study research method, which applies what-if scenarios for each level of LPS-BIM to measure their impacts on MD generation and mitigation. The chapter presented a quantitative formulation for the causal structure of

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the three LPS, BIM, and MD concepts. The case study was applied to test and validate the constructed mode and offered comparative analysis for the studied variables.

Despite notable advancements in this chapter, the automation process holds many potential benefits but has still not been exploited. There is a pressing need for a program that builds in an alternative manner to generate different spreadsheet formats and delivers them in D3M. Furthermore, a direct link with a BIM quantity take-off and 4D timeline scheduling is imperative to enhance and expedite the MD simulations process. Automating the scheduling process and preventing technical errors when the data is entered in the spreadsheet backed up by the Anylogic software saves a substantial amount of time when the collection process is involved in this methodology.

8. Conclusions and Future Works

This chapter summarises this thesis's main conclusions and contribution and recommends an agenda for future work.

8.1. Conclusions

There is an urgent demand to improve the current construction management models, specifically waste elimination frameworks, to provide efficient and effective projects and achieve the UN's shared goals of responsible consumption and production. The construction industry has been recognised as a significant contributor to waste and inefficiency. However, traditional management theory fails to explain waste because it captures a minor element of the construction process that cannot capture the small scale of waste at the operational level nor the production waste, which is undoubtedly a fundamental component of processes, and none of the conventional management theories disputes that.

Traditional approaches to waste management deal with symptoms of production problems that only focus on one type or form of waste without addressing other types collectively. Alternatively, Lean construction centralises waste management in its principles, methods, tools, and techniques by embracing production and waste elimination concepts; the evidence shows that the adoption of LC can reduce material waste, rework, defects, gas emissions, and accidents on construction sites as analysed in Section 2.5.5.

Lean construction literature actively reports the seven types of non-value-added waste (overproduction, overprocessing, inventory, transportation/moving, waiting, defects, and reworks). Making-Do (MD) is believed to be a core and lead type of construction waste that interwinds with other wastes such as poor productivity, rework, transportation, material waste, waiting, overproduction, defects, and loss in labour motivation. MD is a root cause of the behaviour of construction project delays and cost overruns. MD has little research or recognition in the professional and academic arenas, requiring specific and oriented actions of stakeholder awareness and engagement.

It is envisaged that a holistic lean approach can tackle this high-level list of wastes across the whole construction supply chain by adapting Integrated Lean Project Delivery (ILPD). Such adaptation is information-intensive, requiring consistent and reliable information management systems such as BIM in the construction industry. The interaction between LC principles and BIM functionalities has been envisaged as a catalyst for innovative project delivery that eliminates waste and adds value at every stage of construction. The BIM information can manage waste attributes, supporting lean methodologies to invoke waste elimination strategies over the construction life cycle. This discovery of LC-BIM has brought significant improvement in the process of planning and control for the construction production, explicitly intended to embed the Last Planner System (LPS) within 4D BIM, and this idea visualised LPS

8. Conclusions and Future Works

methodology within the BIM ecosystem that can allow the construction project teams to fine-tune the construction plans by the real-time mechanism of assigning production plans to their trades, analysing the construction constraints and recoding the construction progress. However, the current state of the literature shows the potential of LC and BIM to enhance construction efficiency by delivering customer value and addressing waste. However, much work needs to be done to provide more established solutions. Especially since most of the developed LC-BIM solutions are parallel and LPS-BIM strategies toward construction waste elimination have not yet been explored holistically.

Consequently, the dynamic interactions of both concepts for waste elimination are often neglected due to the lack of established policies. With this concern, this research has developed a novel system dynamic approach to examine the LPS-BIM parameter's impact on MD elimination as a decision-making tool regarding production planning and control at earlier planning stages during the development of master plans. Thus, planners will be able to compare different LPS-BIM measures to effectively enhance the production performance and reduce additional construction costs caused by delays and non-value-added activities, so it could eventually help new lean construction and BIM adopters to understand the negative impact of MD and the positive impact LPS-BIM on MD elimination.

This research approached several strategies introduced by the literature, case studies, and questionnaire surveys in Chapters 2, 4, 5, and 6. Those are designed to study the potential impact of LPS and BIM parameters on MD mitigation, which can be introduced to production planning and control functions. The dynamic hypothesis was modelled in Section 4.4 by a causal loop diagram (CLD), that exhibited the casual structure of Making-Do waste and how it impacts other variables in construction projects. The casual loops connect prerequisites, MD causes, MD categories, and impacts. Recognising the critical importance of mitigating the adverse effects of MD waste to fill this knowledge gap, the research revealed the causal structure of MD in construction projects. A generic causal loop diagram connects the dots between production planning and control, quality management, harnessing information technology, and social factor empowerment.

The D3M (Dynamic Model for Making-Do Mitigation) is grouped into functional subsystems, data, dynamic project management parameters, LPS functions, BIM functionalities, and dynamic output. The final production of D3M includes time series graphs for the variables under study. The dynamic yield also includes presenting the stock values for making-do, constraints, wastes, and other parameters in the system.

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Multiple Linear Regression Analysis (MLRA) was employed to establish the relationships between various variables in the D3M tool as follows: WIP ↔ master planning, WIP ↔ constraints among others (as explained in Appendix IV.3. Dynamic system equations). Partial Least Square – Structural Equation Model (PLS-SEM) modelled the relationships between latent variables LPS functions (LPSF), Cooperation (COO), Making-Do Knowledge (MDK), and BIM functionalities (BIMF).

D3M was successfully validated against the traditional assessment process, with results below 7% (as shown in section 7.5.1); it may be caused by the noise from system dynamics approximations or by the regression formulas used across the stock and flow diagrams. The significant differences between traditional and D3M analysis and the advantages and drawbacks are presented in Table 8-1.

Table 8-1 – D3M vs traditional MD analysis

D3M	Traditional MD analysis
The dynamic application accepts changes during the simulation	Static application changes may take more time and error-prone
Automatic and standardised report generation	Manual report generation
Considering different scenarios, multiple projects can be simulated at the same time.	Each scenario and project requires different input and new files.
Import and export Excel files directly for MD and production analysis	Manual data entry and edit
It does not consider some MD categories	Fully considers MD categories
It considers relationships between MD, constraints, waste, and other system variables.	It implicitly considers relationships between MD, constraints, waste, and other system variables.
Shorter analysis time	Long analysis time

The use of the D3M system can be applied during the early stages of project planning to predict production planning system behaviour and make informed decisions; early informing helps to prevent delays and NVA, improving overall project efficiency. D3M deployment is fully operational and can be used in new and old construction projects to accommodate varied scenarios in the sector. Different organisations can employ D3M to recognise how to optimise their construction plans; with this understanding, they can mitigate some of the adverse effects of MD. However, the D3M stages may not perfectly reflect the reality of the project. Regardless, research has shown that the procedure's replicability is practical. The subsystems of D3M may be changed and added only in AnyLogic Software, and the new subsystem can be designed to be similar to or different from the usual process. However, the

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versatility of D3M mirrors the enabling of the replication of research outcomes in other building types and countries with little effort. Additionally, D3M's causal structure and stock flow diagrams used in D3M can also be used to identify different forms of waste, provided they are also based on KPIs.

Among other things, it is noteworthy that the applied software AnyLogic has proven its suitability for the dynamic simulation of MD behaviour. It allows for creating and fixing various lean policies – all data arrays for performance assessment are processed simultaneously. That makes it possible to import and export data onto Excel files. Also, by exporting to a cloud web page, non-licensed users could still assess their production systems by comparing them with MD categories. Moreover, AnyLogic models could be customised by applying customised Java codes, thereby personalising the user experience.

Concerning the research procedure, a slight deviation was noticed from the actual plan. D3M was intended to be divided into four stages and provide a lean policy, as presented in Chapter 3. However, with the research evolution, qualitative data and schedule performance results were noticed to require further observations, access to organisation documents, and additional tools, which was difficult due to the researcher's location and the organisation's privacy that will not access more company documents. Such limitation hinders the possibility of further or more advanced analysis within the ontology of D3M. Additionally, the MD and planning simulations are usually made in a more advanced project stage and need specific knowledge of different project disciplines. Moreover, the result shows the unpredictability of D3M mainly when applying extreme conditions tests, as some of the intended parameters for D3M were not feasible to be modelled.

However, The D3M system can provide real-time feedback by predicting the behaviour of the production system behaviour in the early stages of the project, acting as a decision support tool even for non-experts' construction stakeholders with LPS or MD; it has successfully established a novel and common approach of integrating LPS-BIM at the strategic level for planning and control process, which can serve as a systematic framework to apply LPS in BIM in other contexts, as well as an example of future lean policies for the construction industry. D3M will represent the pathway of reducing construction waste and MD impacts and provide valuable contributions to reaching UN goals by enhancing production efficiency and reducing physical and temporal wastes.

8.2. Practical Implications

According to the research findings of this thesis, the following practical implications are recommended for better construction organisations to enhance efficiency, reduce waste, and improve overall project outcomes:

- **Weekly lean meetings:** It is recommended that managers hold weekly meetings with construction teams to review progress, identify waste, and implement LC principles, using these meetings to address any issues related to overproduction, defects, and waiting times. For example, implementing a “waste walk” during these meetings with the team can help the planning team better assess and discuss potential sources of MD.
- **Use BIM for real-time waste tracking:** use BIM methodology to monitor and report the waste in real-time to enable identification of waste issues and later rectify them as they occur and to decrease the level of waste in the project to incorporate the BIM system and prepare the automated and standard reports in terms of wastes, progress and performance indicators instead of the manual time taking, error-prone documentations.
- **LPS implementation:** explain how to teach the LPS to train project managers and site supervisors on how best to incorporate the LPS with BIM to enhance the development of weekly work schedules and plans and also how best to ensure that tasks are accomplished appropriately and on time while optimally utilising resources and organising workshops focused on the practical application of LPS and BIM for MD mitigation, inviting experienced professionals to share their experience and best practices, utilising knowledge transfer within the market. A training program structured on simulations and real-world case studies will be needed. The program should essentially focus on lean construction and especially on the basic elements of the LPS, such as lookahead planning, constraints analysis, and short-term planning, demonstrating how 4D BIM can improve the application of the LPS.
- **Anylogic dynamic simulation** enables the evaluation of the impact of waste on project plans by creating several scenarios. Dynamic simulation could facilitate enhanced strategic management by providing insights on organisational plan development as well as decision-making concerning the execution of the project to achieve maximum efficiency and reduce waste.
- **Real-time integration:** establishing a shared information environment where data from different sources could be fed into the BIM environment for further decision-making about waste and

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other factors that may impact the project.

- Stakeholders training programs: Subcontractors, suppliers, and designers should undergo training sessions on waste elimination and correct use of LC and BIM tools regularly.
- Early detection of constraints: D3M helps reveal constraints early in the project, which aids in minimising MD and related waste. D3M can help avoid MD practices and their associated consequences by analysing various alternatives, such as the construction of MEP and HVAC components; it could identify potential clashes between trades, material delivery delays, or lack of access to equipment.

8.3. Future works

This section offers an agenda for further development and suggests solutions for unaddressed points in this thesis and future research works can be summarised as follows:

Regarding addressed parameters Regarding the suggested LC-BIM

- The investigated variables and their parameters (i.e., LPS technical, collaboration, Making-Do Knowledge, and BIM functionalities parameters) require a deeper investigation into how each parameter may impact the other. Some relationships were hypothesised but, through this research, were found insignificant according to SEM results. Further exploration of relationships between these parameters, especially between BIM and Making-Do, is recommended because when the system dynamic was applied, BIM had a real impact on MD mitigation and dramatically enhanced the performance of the production planning systems.
- Regarding the current LC-BIM approaches to address waste in construction, there is a need to research real-time data analysis methods to explore how various technologies could be applied. For instance, an AI-powered system that integrates data from BIM models, LPS schedules, material tracking systems, and even real-time weather information could be a future development that enhances the current waste elimination methods. By analysing this data, the AI could identify potential MD scenarios before they occur. For example, if a delay in material delivery coincides with a critical task in the LPS schedule, the AI could alert project managers and suggest proactive interventions, such as adjusting the schedule, securing alternative materials, or reallocating resources. Similarly, a Digital Twin, a dynamic virtual representation of a physical asset or process, could simulate the impact of these interventions, allowing project teams to make informed decisions that minimise disruptions

and prevent Making Do waste.

- Regarding the methodology: Regression analysis was used extensively in this research and held high accuracy in mathematically modelling the relationships between various variables depending on the quality of data within the provided system dynamics model, particularly those previously established in the literature. System dynamics theory emphasises that systems are more effectively represented through dynamic, multi-directional, and non-linear feedback loops rather than linear models. Traditional linear regression models often fail to capture the dynamic complexity unless tailored approaches are used. Future research can investigate the utilisation of machine learning (ML) algorithms to manage complex and nonlinear relationships better than regression models, considering the algorithms used, the data quality, and the problem being modelled.
- System dynamics itself has outstanding results when strategic policies are investigated. The evidence in this research shows how it can be used to model problems and compare different strategies to improve the system structure to respond to these problems. However, the major limitation of SDM is the low level of detailing and high abstraction within its functions, which should not be used alone when operational-level variables are studied. A multi-level simulation methodology can overcome this limitation; for example, applying Agent-Based Modelling (ABM) and Discrete Event Simulation (DES) can enhance the simulation outcomes by including further details of the system components.
- Validation of the D3M framework through case studies that utilise LPS-BIM for the first time is highly recommended for future research, where a comparison that quantifies MD levels before and after adoption would give further contributions towards the study of MD and extends the LPS application when BIM is integrated.
- D3M must be extended to include other buildings like offices, schools, clinical centres, or health care. Initially, it is advisable to discover alternative stages and sub-stages for possible incorporation or discarding from the existing structure of D3M.
- The optimisation of the D3M algorithm is necessary to reduce the assessment time of large and complex buildings. With the expansion of knowledge, new simulation algorithms are bound to emerge, and these techniques can be implemented to enhance existing algorithms by utilising new ideas.
- Incorporating the remaining Making Do constraints and waste categories into D3M is essential. As the software development and informatics field keeps thriving, D3M will adapt

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and implement all principles, enabling users to evaluate MD dynamics and details in seconds.

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I. Appendix A: Questionnaire Survey

Making-Do Waste in the Construction

Greetings, I'm Mahmoud Karaz, a PhD candidate from the University of Minho, currently engaged in research on lean construction. Specifically, my study focuses on the impact of the Last Planner System (LPS) and Building Information Modelling (BIM) on comprehending and addressing **Making-Do Waste***.

Your participation in this questionnaire is significant and I sincerely appreciate your involvement.

The questionnaire is divided into four sections.

***Making-Do Waste: This refers to tasks without optimal inputs, such as materials, labour, information, external conditions, space, equipment or tools and the sequencing of finishing activities.**

Please be assured that your responses will be treated with the utmost confidentiality and anonymity. Once the research is concluded, all data will be securely destroyed.

Thank you for contributing your valuable insights to this research.

Example of making-do impact (courtesy: Sacks et al. 2017)



Example of making-do impact (courtesy: Formoso et al. 2017)



Section A: Demographic characteristics

Section A: Demographic characteristics

1. What is your experience in the industry (years)?* **Mark only one choice.**

Mark only one box with (X)

- ☐ 0-5
- ☐ 6-10
- ☐ 11-15
- ☐ 16-20
- ☐ 21-25
- ☐ 25 and more

2. What is your education level?* **Mark only one choice.**

Mark only one box with (X)

- ☐ 0-5
- ☐ 6-10
- ☐ 11-15
- ☐ 16-20
- ☐ 21-25
- ☐ 25 and more

What is your job title? * **Mark only one choice.**

Mark only one box with (X) and type in the "other" field if your job title is not enlisted here.

- ☐ Project Manager
- ☐ Superintendent
- ☐ Estimator
- ☐ Field Engineer
- ☐ Quality Control
- ☐ Safety Coordinator
- ☐ Document Control
- ☐ Bid Coordinator
- ☐ Procurement Specialist
- ☐ Designer
- ☐ Other: _____

Section B: Knowledge and Experience in Lean Construction and BIM

1. Have you ever participated in a Lean Construction course, training, workshop, or seminar? *

Mark only one box with (X)

- ☐ Yes
- ☐ No

2. Have you ever participated in a BIM course, training, workshop, or seminar? *

Mark only one box with (X)

I. Appendix A: Questionnaire Survey

☐ Yes

☐ No

3. Years of using BIM in your workflow? *

Mark only one box with (X)

☐ No use

☐ 1-5

☐ 6-10

☐ 11-15

☐ 20 and more

4. Have you used Lean Construction in your workflow for years? *

Mark only one box with (X)

☐ No use

☐ 1-5

☐ 6-10

☐ 11-15

☐ 20 and more

5. How long have you used the Last Planner System (LPS) in your workflow? *

Mark only one box with (X)

☐ No use

☐ 1-5

☐ 6-10

☐ 11-15

☐ 20 and more

Section C: Knowledge and Experience with Making-Do

1. Have you ever heard of Making-Do waste or a similar concept? *

Mark only one box with (X). If your company has different terminology for such practice, please type in another field.

☐ Yes

☐ No

☐ Other: _____

2. Identify the project participants involved in Making-Do incidents.

Check all that apply (X). If you think the other party is responsible, please mark the different fields with X

I. Appendix A: Questionnaire Survey

and type the missing party.

- ☐ Clients
- ☐ Regulators
- ☐ Project Managers
- ☐ Suppliers
- ☐ Specialty Trades
- ☐ Consultants
- ☐ Designers
- ☐ Others: _____

Section D: Strategies to manage Making-Do practices

How important are the following strategies in mitigating Making-Do waste and its impacts?

Mark only one per row (1-Not Important, 2- Less Important, 3- Moderately Important, 4- Important, 5- Most Important)

	1	2	3	4	5
1. Handle disagreement and interests.					
2. Ensure high-level coordination					
3. Enable discussions					
4. Local adjustments to fit organizations					
5. Coaching, training and arranging seminars for the superintendent and foreman					
6. Process and transform knowledge from experience.					
7. Generate a data bank to attribute misinterpreted principles of Making-Do, Lean construction and the Last Planner System.					
8. Learn from breakdowns					
9. Exchange experience among companies					
10. Comparing with the number of cases how MD is handled					
11. BIM models, design drawings and site layout plans are available for the team to reference during the LPS					
12. Keep all plans in public view.					

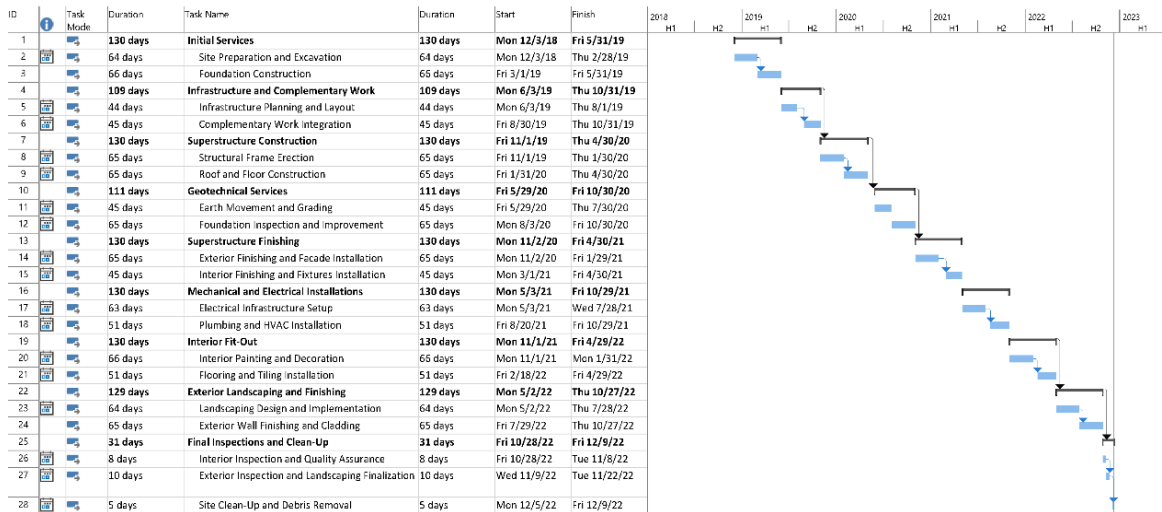
I. Appendix A: Questionnaire Survey

13. Using Guiding information across digital and physical environments					
14. Constraints analysis of all activities is applied as a proactive approach to problem-solving as a team.					
15. Delay tasks that their constraints are unresolved or unknown					
16. Urge stakeholders to share constraints that can hurdle their communication.					
17. Engage stakeholders in constraints management.					
18. Maintaining a workable backlog of operations					
19. Task breakdown from processes to operations and operations to tasks					
20. Collaborative digital prototyping of operations design using BIM					
21. Daily discussion between trades about their constraints					
22. Utilise 4D planning to illustrate constraints and relate them with time.					
23. Visualise task information following product information.					
24. Detect time and space clashes using BIM tools.					
25. Exchange and communicate BIM models online					

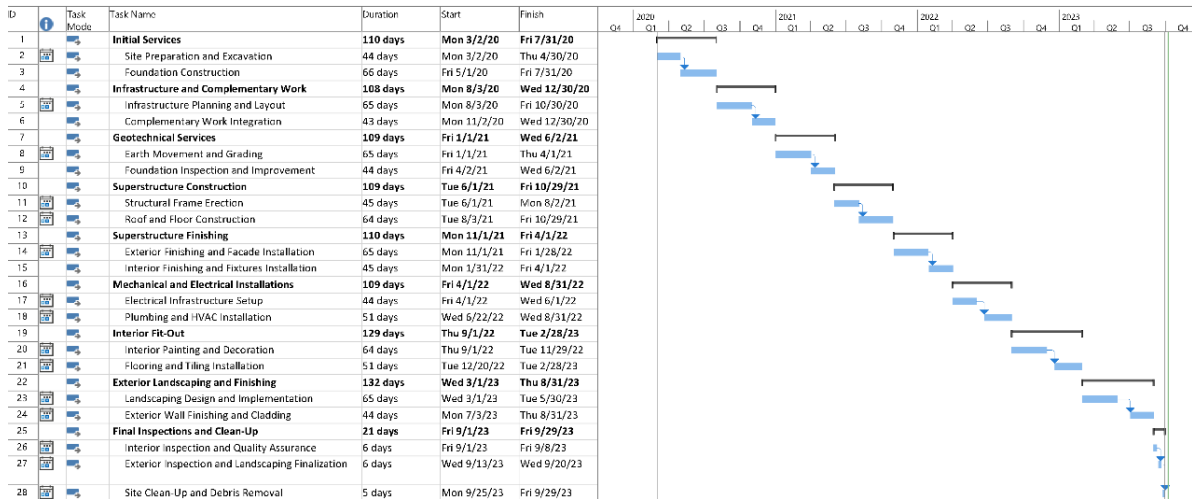
II. Appendix B: Master Schedules of the Case Studies

II. Appendix B: Master Schedules of the Case Studies

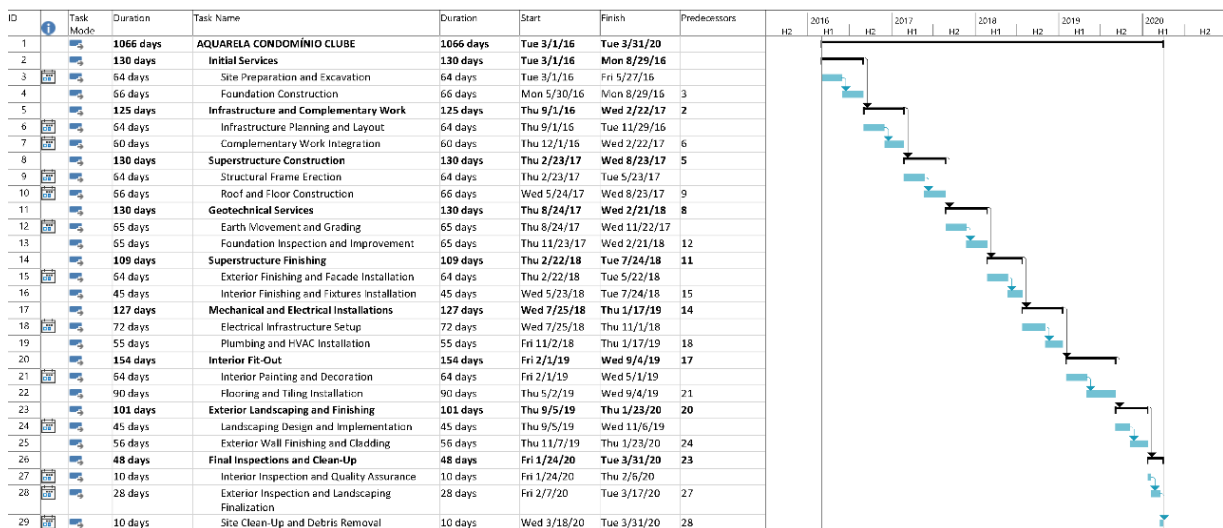
Project A



Project B



Project C



III. Appendix C: D3M User Guide

III.1. Context

D3M initially emerged through a dissertation within a research initiative focused on assessing the potential effects of Making-Do (MD) on production practices and construction outcomes. Furthermore, it delves into the possible advantages of merging the LPS and BIM for production planning and control.

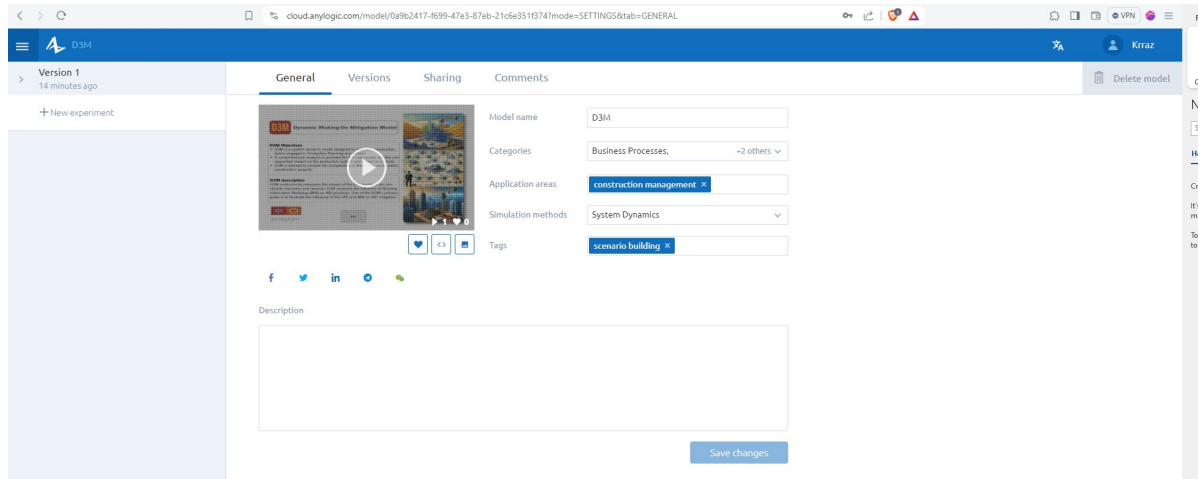


Figure III-1 – Cloud application of D3M.

Figure III-2 is a snapshot of the welcome message once the model is opened; the message contains a brief introduction with objectives of the model development and simulation and a short description of how D3M can be helpful to the user once the run button is clicked.

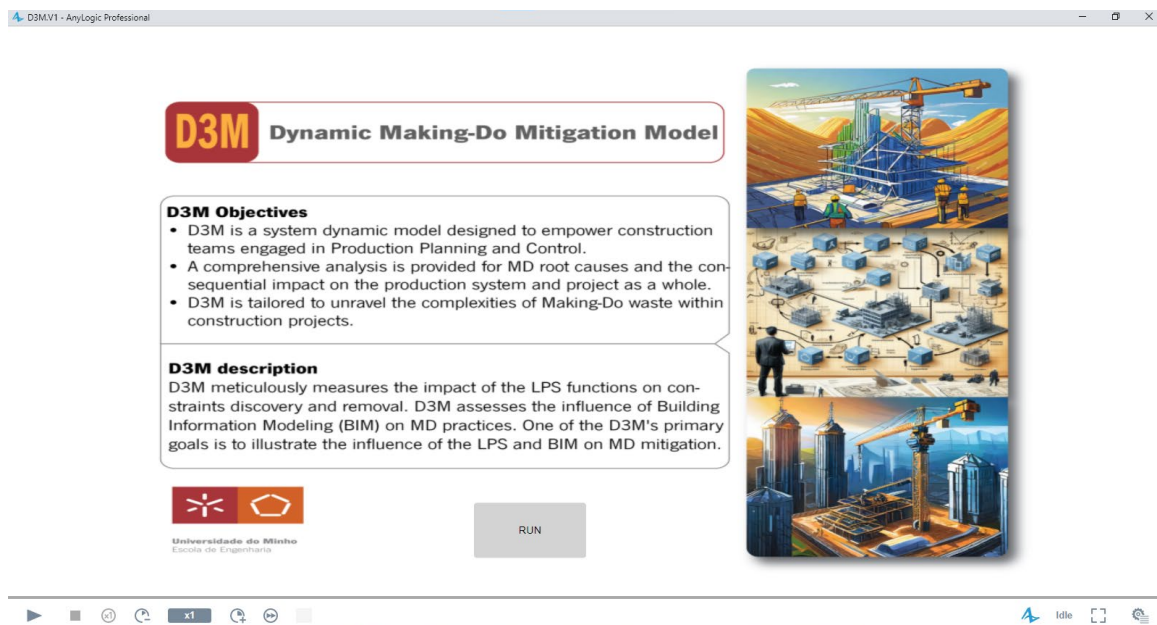


Figure III-2 – D3M Welcome Message

III. Appendix C: D3M User Guide

D3M provides a direct assessment of 25 strategies from LPS-BIM and suggests additional pathways to formulate lean-based policy, as presented in Figure III-3.

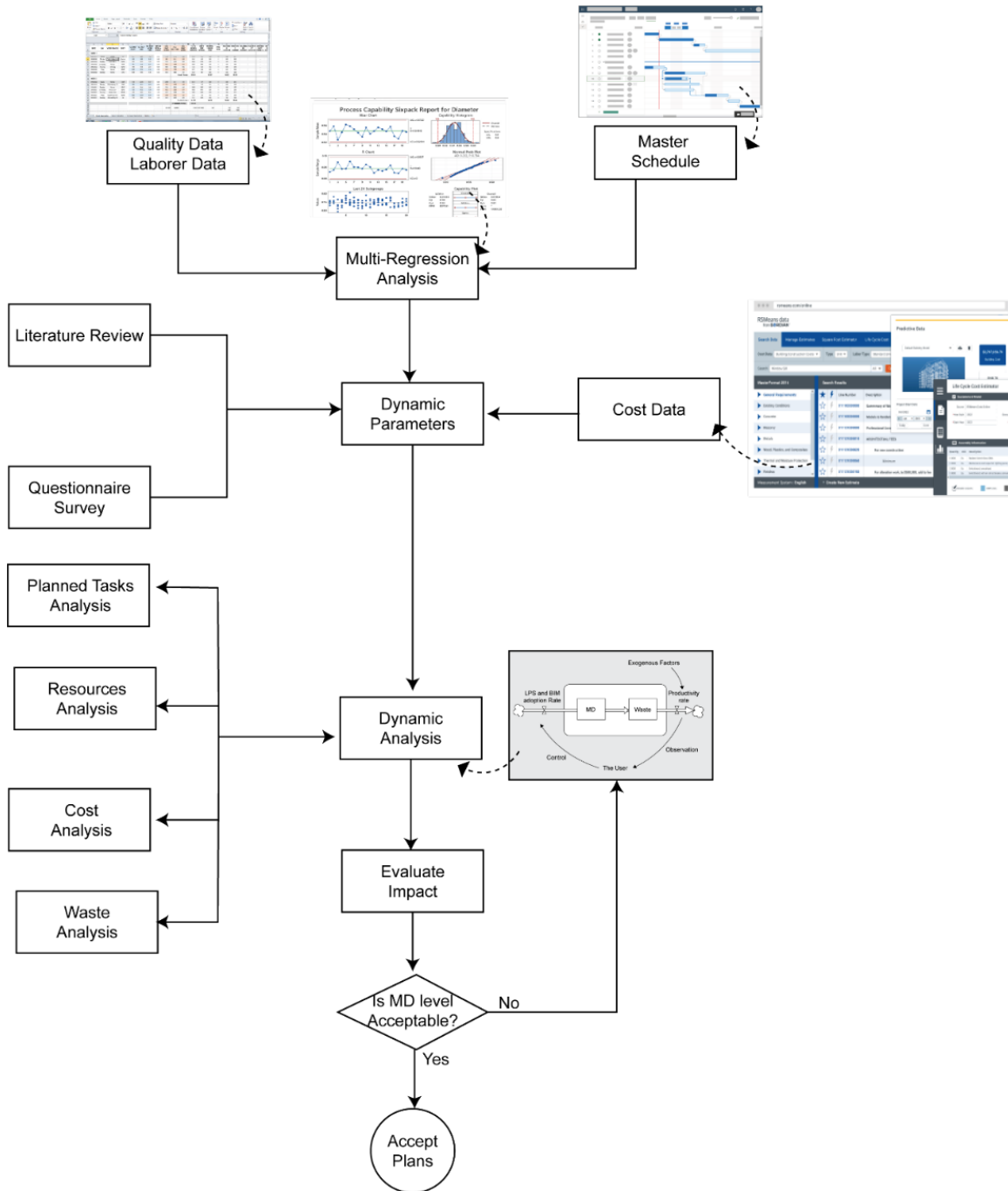


Figure III-3 – The dynamic framework for MD waste analysis.

III. Appendix C: D3M User Guide

Table III-1 delineates each strategy used by D3M, where the parameters and their coefficients were used in the D3M system. All parameters had their weights distributed by considering the estimation results of the SEM mediation analysis. Moreover, the relationship between variables is applied, MDK influenced by LPSF_F, COO_F exerting influences LPS_F and influenced by BIMF_F.

Table III-1 – Parameters of LPS-BIM within D3M

Component	Parameter	Coefficient	Formula
LPS_F	VA10	9.8%	
	VA11	7.2%	
	VA12	7.7%	
	VA13	7.4%	
	VA14	7.3%	(0.098* VA10 + 0.072 * VA11 + 0.077 * VA12 + 0.074
	VA15	8.4%	* VA13+ 0.073 * VA14 + 0.084 * VA15 + 0.072 * VA16 +
	VA16	7.2%	0.064 * VA17 + 0.057 * VA18 + 0.071 * VA19 + 0.077 *
	VA17	6.4%	VA20) + 0.106 * COO_F
	VA18	5.7%	
	VA19	7.1%	
	VA20	7.7%	
COO_F	COO_F	10.6%	
	VA1	5.7%	
	VA2	6.7%	
	VA3	5.5%	(0.057 * VA1 + 0.067 * VA2 + 0.055 * VA3 + 0.083*
	VA4	8.3%	VA4) + 0.160 * BIMF_S
MDK	BIMF_S	16%	
	VA5	8.5%	
	VA6	4.7%	
	VA7	5.5%	(0.85 * VA5 + 0.047 * VA6 + 0.055 * VA7 + 0.057 * VA8
	VA8	8.1%	+ 0.081 * VA9) + 0.116 * LPSF_F
BIMF_F	LPSF_F	11.6%	
	VA21	12.5%	
	VA22	7%	
	VA23	5.5%	(0.125 * VA21 + 0.070 * VA22 + 0.055 * VA23 + 0.061
	VA24	6.1%	* VA24 + 0.077 * VA25)
	VA25	7.7%	

III. Appendix C: D3M User Guide

D3M was fully developed by System dynamics modelling using Java codes and hosted by AnyLogic 8 Professional 8.7.11.

This document serves as a guide for the best practice of D3M. The information in this document does not fully replace a careful understanding of LPS and BIM methods.

Duration in Months

42.0

Estimated Area in squared meters

2860.0

Master Plan Milestones	
Structure	
Walls and Panels	
Cladding and Finishing	
Fixture and Fittings	
Work Completion	

Human Resources Estimation			
Carpenters	10	Plastrereres	50
Electricians	10	Plumbers	20
Engineers	5	Procurment team	6
Glaziers	10	Safety Team	10
Masons	20	Helpers/Servants	30
Painters	20	TileSetters	20
		Builders	15

Figure III-4 – User input window.

Figure III-5 (a) illustrates the options of preset inputs for the scenarios of extreme value simulation, comprising six buttons. Figure III-5 (b) is an example of code used to set all LPS-related parameters in scenarios A to 5 as the maximum value of the Likert scale used throughout the simulation and following SEM results.

Scenario A (LPS parameters ON)

Scenario B (Collaborative LPS parameters ON)

Scenario B-2 (Only Collaborative ON)

Scenario C (MD knowledge ON)

Scenario D (Full LPS-BIM)

Scenario D-2 (Only BIM is ON)

Name:

button8

☐ Ignore ☒ V

Label:

Scenario A (LPS parameters ON)

Enabled: ☒ yes

Action

set_VA10(5);

set_VA11(5);

set_VA12(5);

set_VA13(5);

set_VA14(5);

set_VA15(5);

set_VA16(5);

set_VA17(5);

set_VA18(5);

set_VA19(5);

set_VA20(5);

(a)

(b)

Figure III-5 – preset buttons for extreme value tests.

III. Appendix C: D3M User Guide

Another option to allow users to test variations of the studied parameters is available through sliders, as shown in Figure III-6.

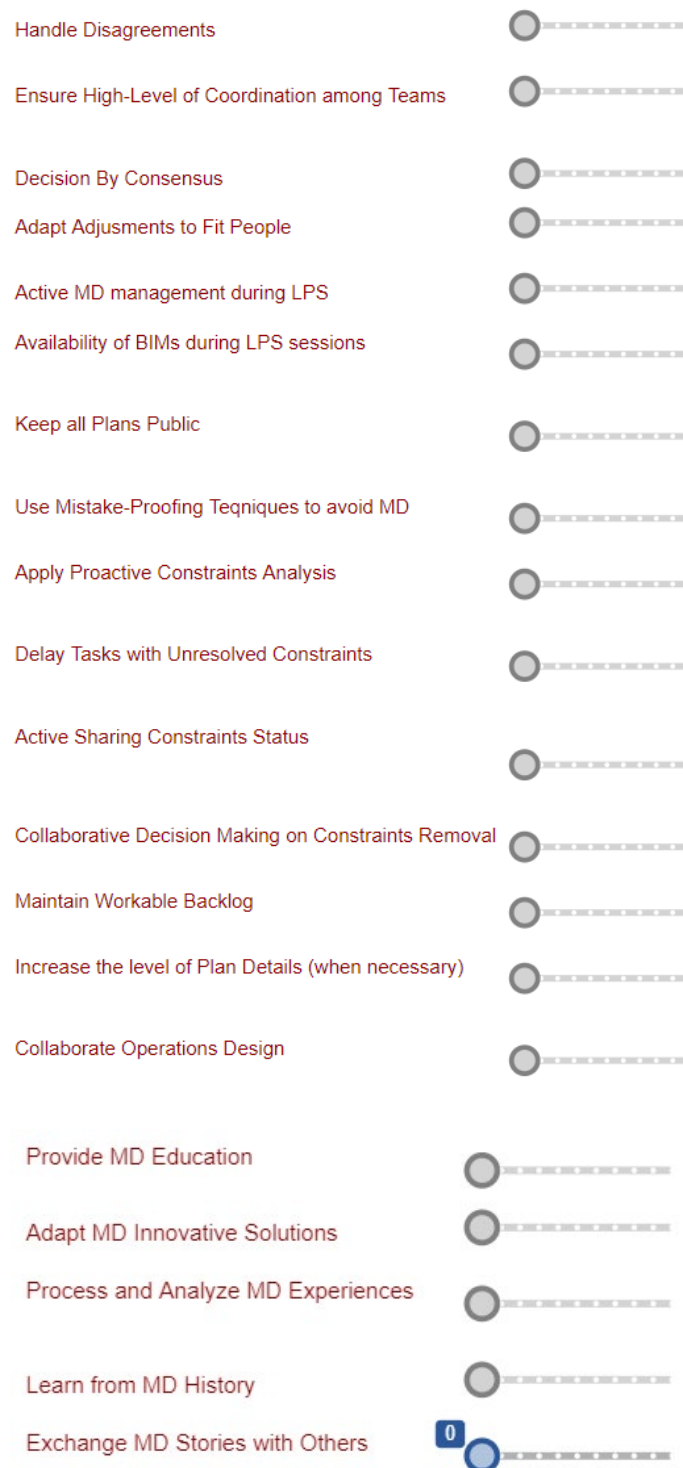


Figure III-6 – Slider controllers to set parameter values.

D3M research was funded by the Portuguese Foundation for Science and Technology (FCT), with grant number 2021.04751.BD

III.2. D3M folder

The D3M folder must not be downloaded to the computer if the user is not using Anylogic software. In case the user holds an Anylogic license, the following files are included:

- Executable D3M file (*.alp)
- Welcome message (*.png)
- D3M Excell spreadsheet (*.xlsx)
- D3M database folder (db.properties) and (db. script)
- D3M User Guide (*.pdf)

III.3. D3M guidelines and outputs

To start using D3M, a master plan is required. The dynamic model can be edited or modified in AnyLogic 8 Professional 8.7.11 or later.

III.3.1. D3M guidelines

The system dynamic model should be run through some user input data that must include the following:

- Estimated finish date for each stage or milestone.
- Estimated duration in months.
- Estimated number of resources used.
- Scale of LPS-BIM parameters 1 to 5.

III.3.2. D3M output

The most vital feature of D3M is not only the simulation for stock and flow diagrams but also real-time information presented in the control dashboard that shows the stored values of constraints, making do incidents and wastes in the (Tasks) unit (As given in Figure III-7).

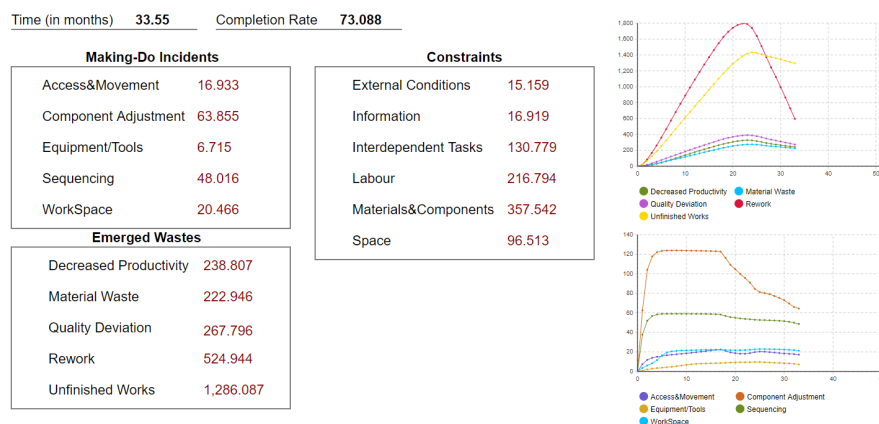


Figure III-7 – D3M dashboard.

III. Appendix C: D3M User Guide

Figure III-8 (a) represents how many stages are planned according to the master schedule. (b) showcases the number of tasks in WIP stock and (c) the number of discovered constraints. (d) The progress of finished works is categorized into substages: (e) the number of tasks that emerged wastes and (f) the number of MD incidents categorized.

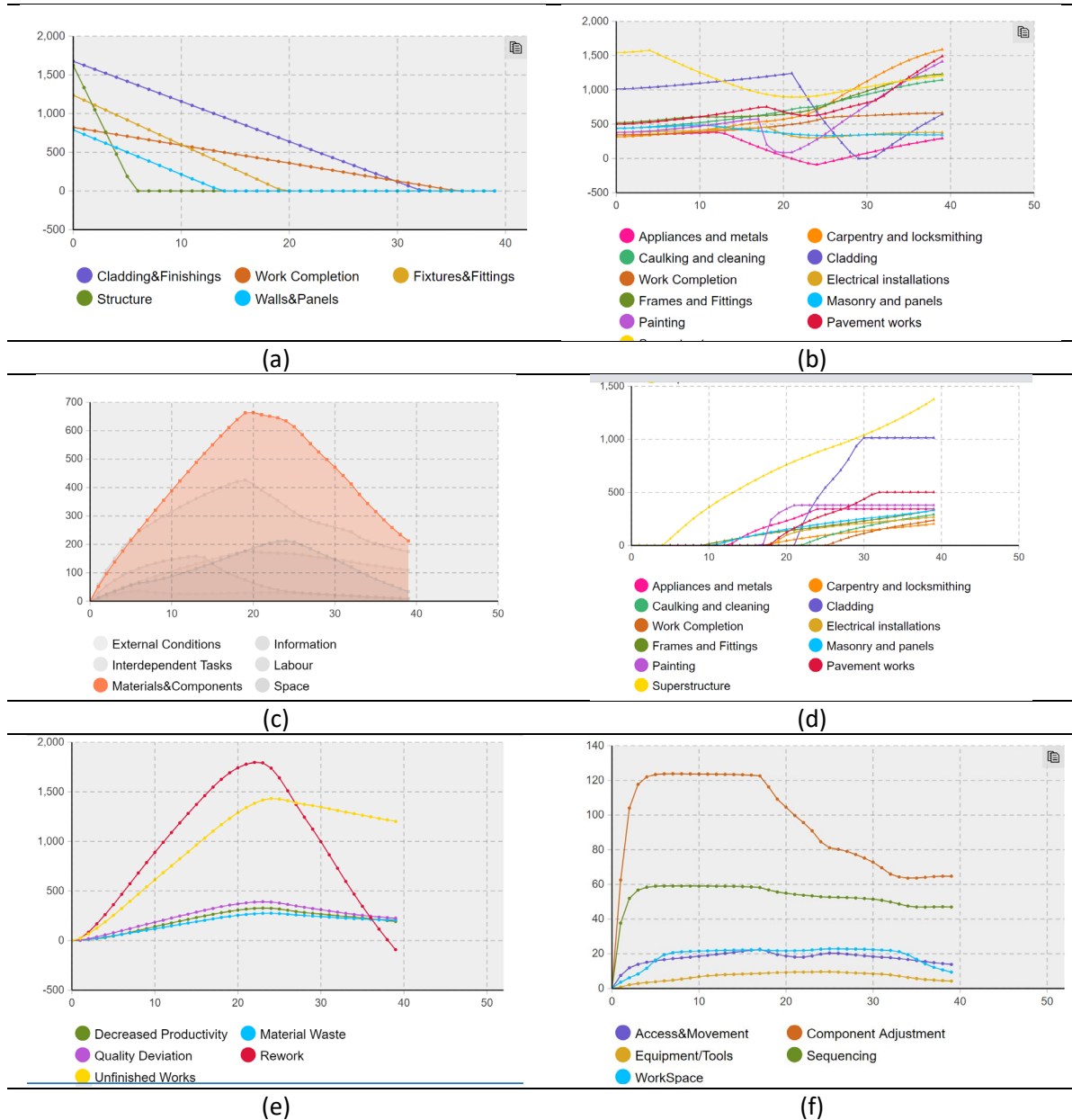


Figure III-8 – Control charts of D3M.

The first page of stock and flow diagrams, presented in Figure III-9, shows the work progress located. The panning cursor / will be activated by pressing on the scrolling roll. (a) represents the master schedule information, (b) the interaction between WIP, finished works and constraints and (c) includes the socks of making do and wastes. Each stock in this figure should be working and it is necessary to

III. Appendix C: D3M User Guide

identify the area of construction, milestones dates and expected finish dates for each substage to constrain the model into real-world behaviour.

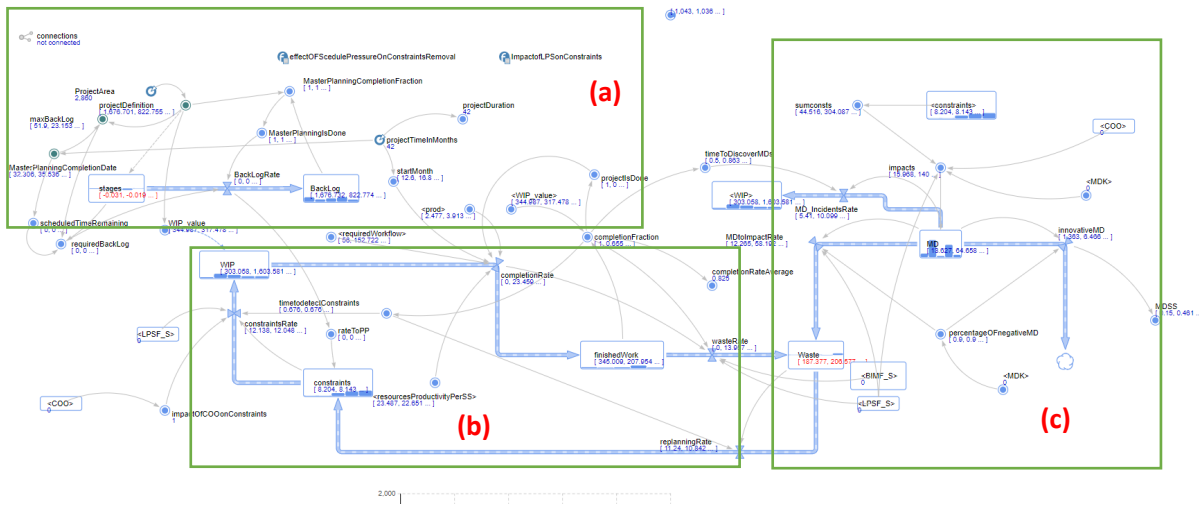


Figure III-9 – Work progress and MD subsystems.

Figure III-10 illustrates the space management system; the essential value is the workspaceAvailable variable because this variable will be used to calculate productivity.

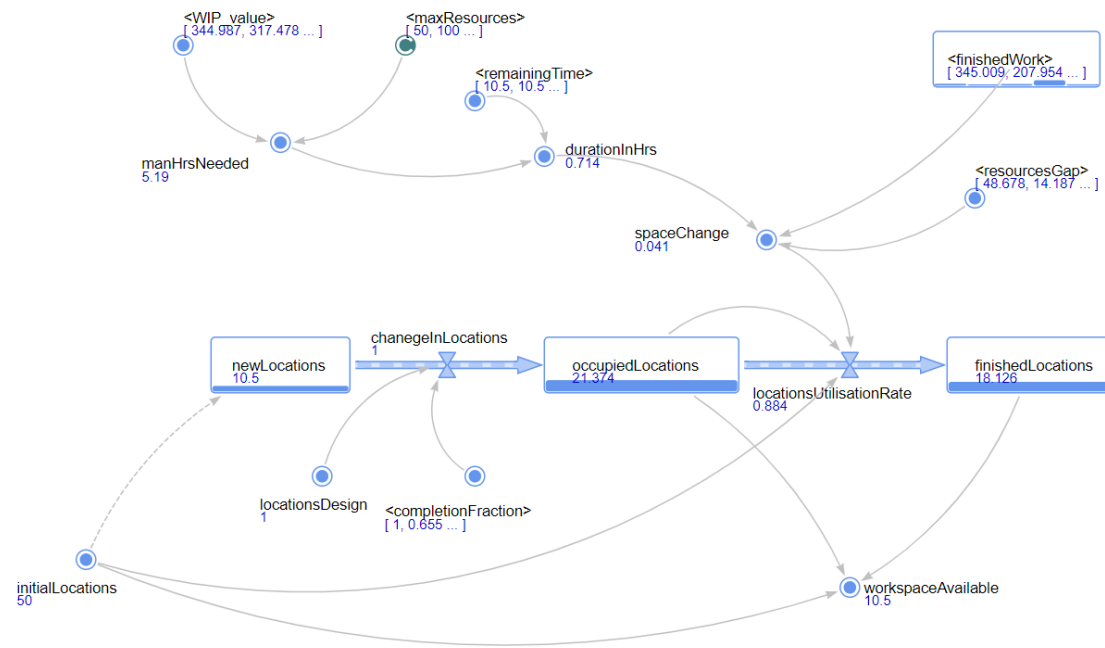


Figure III-10 – Location subsystem.

The figure below describes the impact of resources on productivity and spaces, $TimeToIncreaseWorkforce$ and $resourceAdjustmentTime > 0$; it must be more than 0 when needed. LPS, BIM and COO parameters have an impact on resource Efficiency. Part (a) represents the impact of workflow on resources; RR is the conversion between units (tasks) to (person); (b) this section

represents the core part of the resources subsystem; (c) is the most vital part where it connects the relationship from resources to the productivity rate.



Figure III-12 showcases how schedule pressure affects productivity (prod), overtime, workflow, space limitation and MD decisions are included in productivity calculation.



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IV.1. Evaluated LPS-BIM Parameters

Table IV-1 explains the parameters of LPS-BIM, which are strategies to mitigate MD and increase the adoption of LPS-BIM.

Table IV-1 – Parameters explanation and scale

ID	Factor	Explanation	Rating Scale
VA1	Handling conflicts among various stakeholders	This parameter measures how the team can address conflicts among diverse stakeholders in resolving disputes about responsibility for constraints and the mechanisms employed for their removal.	Likert 1-5
VA2	Coordination level	This input specifies the percentage of coordination implemented during Last Planner System (LPS) sessions.	Likert 1-5
VA3	Enabling discussions	This parameter specifies the level of opening discussions, how project management encourages dialogue among relevant parties during the planning phase and the resolution of their tasks within lookahead and make-ready planning sessions.	Likert 1-5
VA4	Local adjustments to organisations	This parameter encompasses the modifications made to accommodate the Last Planner System in alignment with the organisation's culture, resources, projects, priorities, goals and visions.	Likert 1-5
VA4	Engagement in constraints analysis	This parameter enables users to designate the degree of involvement for each trade in the constraints analysis process. A heightened level of engagement can result in more reliable plans and a reduction in MD practices when constraints are removed correctly and collaboratively.	Likert 1-5

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VA5	Coaching and training	The level of instruction provided to superintendents and crew leaders in collaborative pull planning. It also encompasses assessing how planners prepare for and sustain the implementation of the LPS.	Likert 1-5
VA6	Processing MD data	Process and translate knowledge from experiential learning into actionable insights.	Likert 1-5
VA7	Data bank for LPS and MDs	This parameter specifies if the data repository for MD incidents is comprehensively used to detail each occurrence, including its unique identifier (ID), timestamps for the incident history, MD category, associated constraints, root cause analysis, involved trades, location, process name, operation details, task specifics, MD impact and any countermeasures employed if corrections were made.	Likert 1-5
VA8	Learn from past incidents of MD	This parameter measures how the enterprise learns from historical data for MD.	Likert 1-5
VA9	Exchange experiences with other enterprises	This parameter measures the level of exchanging successful and unsuccessful stories and experiences with other enterprises. And comparing MD records and experience with other enterprises	Likert 1-5
VA10	Measure plan performance	This parameter is dedicated to assessing the reliability of trade commitments towards LPS measurements for planning performance.	Likert 1-5
VA11	BIM models available during LPS sessions	This parameter measures how much the LPS team employed the most up-to-date BIM models to facilitate the essential information required for task planning and execution.	Likert 1-5
VA12	Keep all plans public.	This parameter measures planning transparency and how much the planning outcomes are shared with the public.	Likert 1-5

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VA13	Communicate instructional and actionable information	This parameter measures the communication level of awareness information about MD and other production wastes among the project participants	Likert 1-5
VA14	Constraints analysis and removal	The parameter specifies the percentage of constraints analysis applied by the LPS team.	Likert 1-5
VA15	Delay uncertain tasks	Delay tasks with uncertain constraints to avoid potential disruptions.	Likert 1-5
VA16	Encourage constraints collaboration	Encourage stakeholders to communicate and share any constraints that may impede progress.	Likert 1-5
VA17	Daily discussion of constraints during daily huddle meetings	This parameter specifies the percentage of daily meetings between workers and superintendents. These meetings involve discussions on planned and completed tasks, addressing technical task execution details. Workers also directly report the daily work output from the previous day, highlighting any encountered constraints during execution.	Likert 1-5
VA18	Maintain workable backlog	This parameter ensures the availability of work for execution ahead of time, preventing engagement with constrained tasks. Tasks located in this backlog are more likely to be free from constraints.	Likert 1-5
VA19	Break down work packages to an actionable level of detail	This parameter measures how much the LPS hierarchy is followed, particularly for highly uncertain critical tasks. MD practices should be classified within the publicly discussed LPS hierarchy during LPS sessions.	Likert 1-5
VA20	Collaborative design for operations	This parameter measures how much effort the team put into exploring various constraints scenarios and anticipating potential issues MD before execution.	Likert 1-5

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VA21	Utilising color-coded visualisation to represent task status	This parameter denotes the percentage of visualisation utilised for tracking task status in response to Andon signals. It encompasses embedded types of constraints associated with tasks and reported MD issues. Additionally, this parameter reports visualised information used by white-collar personnel for data collection and offers guidance on task execution or problem resolution.	Likert 1-5
VA22	Utilise 4D BIM for the tasks at the last planner hierarchy.	This parameter quantifies the percentage of planning details incorporated into the 4D BIM. It is advisable to enhance the level of 4D planning in alignment with the LPS hierarchy.	Likert 1-5
VA23	Align product and process information	Report task information in alignment with product specifications to ensure accuracy. Facilitating the incorporation of MD and constraints information within BIM construction management and authoring software is essential. This parameter measures the percentage of MD information a project team integrates into the parametric BIM model.	Likert 1-5
VA24	Apply clash detection analysis to discover spatial constraints.	This value represents the percentage of applied clash detection across a project. This BIM functionality is recommended to prevent spatial clashes between the works of different trades. Additionally, it can assist decision-makers in determining the sequencing among operations.	Likert 1-5
VA25	Online communication using BIM cloud services	This parameter specifies the percentage of communications performed over BIM cloud services to exchange production information on developed BIM models by design teams with site management, crew leaders and crews.	Likert 1-5

IV.2. Arrays Dimensions

Table IV-2 describes the definition of arrays used in this thesis and also shows the categories.

Table IV-2 – Array dimensions used in the Anylogic

Dimension	Dimension Description	ID	Dimension Element Value
IMPACTS	This dimension collects five impacts of MD in one array and is connected with Constraints stock, MD stock and finishedWorks stock.	I1	Decreased Productivity
		I2	Material Waste
		I3	Quality Deviation
		I4	Rework
		I5	Unfinished Works
CATEGORIES	This dimension collects five categories of MD in one array, connected with Constraints stock, Waste stock and WIP stock.	CAT1	Access&Movement
		CAT2	Component Adjustment
		CAT3	Equipment/Tools
		CAT4	Sequencing
		CAT5	WorkSpace
RESOURCES	This dimension collects 12 human resources, mainly used to calculate the efficiency of each resource, the productivity in each substage and occupied locations. It indirectly impacts the completion rate and The removal of constraints.	R1	Carpenters
		R2	Electricians
		R3	Engineers
		R4	Glaziers
		R5	Masons
		R6	Painters
		R7	Plasterers
		R8	Plumbers
		R9	Procurement team
		R10	Safety Team
		R11	Helpers/Servants
		R12	TileSetters
SUBSTAGES	This array dimension breaks down STAGES into 11 substages, according to the collected data from the	SS1	Appliances and metals
		SS2	Carpentry and locksmithing
		SS3	Caulking and cleaning
		SS4	Cladding

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STAGES	documents acquired from the studied cases in Chapter 7 and Chapter 6	SS5	Work Completion
		SS6	Electrical installations
		SS7	Frames and Fittings
		SS8	Masonry and Panels
		SS9	Painting
		SS10	Pavement works
	This array dimension collects five stages representing the number of works at each stage during the master planning.	SS11	Superstructure
		S1	Cladding&Finishings
		S2	Work Completion
		S3	Fixtures&Fittings
		S4	Structure
CONSTRAINTS	This dimension collects six task constraints that may be encountered in a construction project. It plays a vital role in increasing or reducing the number of generated MDs. Also, it is influenced by wastes encountered and planned activities.	S5	Walls&Panels
		P1	External Conditions
		P2	Information
		P3	Interdependent Tasks
		P4	Labour
		P5	Materials&Components
		P6	Space

IV.3. Dynamic system equations

Table IV-3 mentions the dynamic equations used to define the relationships among the different components of the D3M model.

Table IV-3 – Dynamic equations

ID	Dynamic Variables			Equations	unit
DE1	Change	in		$(0.057 * VA1 + 0.067 * VA2 + 0.055 * VA3 + 0.083 * VA4) + 0.160 * BIMF_S$	1/time
DE2	Change	in	BIM functionalities	$(0.125 * VA21 + 0.070 * VA22 + 0.055 * VA23 + 0.061 * VA24 + 0.077 * VA25)$	1/time
DE3	Change	in	LPS functions	$(0.098 * VA10 + 0.072 * VA11 + 0.077 * VA12 + 0.074 * VA13 + 0.073 * VA14 + 0.084 * VA15 +$	1/time

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		0.072 * VA16 + 0.064 * VA17 + 0.057 * VA18 + 0.071 * VA19 + 0.077 * VA20) + 0.106 * COO_F LPSF_S + BIMF_S >=50 ?	
DE4	Waste reduction rate	wasteGenerationRate(completionFraction[SUBST AGES]) * completionRate[SUBSTAGES]*0.7 : wasteGenerationRate(completionFraction[SUBST AGES])	unitless
DE5	Innovative MD rate	MD[CATEGORIES]*(1- percentageOfNegativeMD[CATEGORIES])	unitless
DE6	MasterPlanningComple tionFraction	zidz(BackLog[STAGES],projectDefinition[STAGES])	unitless
DE7	MasterPlanningIsDone	MasterPlanningCompletionFraction[STAGES] >= 1? 1:0	unitless
DE8	scheduledTimeRemaini ng	MasterPlanningCompletionDate[STAGES]-time() <=0 ? 0:	time
DE9	maxBackLog	MasterPlanningCompletionDate[STAGES]-time() zidz(projectDefinition[STAGES],MasterPlanningC ompletionDate[STAGES])	Task/time
DE10	MasterPlanningComple tionDate	projectTimeInMonths * mastertimeCompletionPercentage[STAGES]	time
DE11	BackLogRate	MasterPlanningIsDone[STAGES]>=1? 0:requiredBackLog[STAGES]	Task/time
DE12	rateToPP[CONSTRAIN TS]	BackLogRate[STAGES]	Task/ time
DE13	WIP_value [SUBSTAGES]	projectDefinition[STAGES]	Task
DE14	constraints	replanningRate[CONSTRAINTS] - constraintsRate[CONSTRAINTS] + rateToPP[CONSTRAINTS]	Task

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		LPSF_S <=60? zidz(constraints[CONSTRAINTS], timetodetectConstraints[CONSTRAINTS]):	
DE15	constraintsRate[CONSTRAINTS]	zidz(zidz(constraints[CONSTRAINTS], timetodetectConstraints[CONSTRAINTS]), impactOfCOOonConstraints * ImpactofLPsonConstraints(LPSF_S))	Task/time
DE16	timetodetectConstraints	effectOFScedulePressureOnConstraintsRemoval (completionFraction.average())	time
DE17	sumconsts[CATEGORIES]	constraints[CONSTRAINTS]	Task
DE18	manHrsNeeded	zidz(WIP_value.average(),maxResources.average() ())	Task/Person
DE19	TaskPerPersonPerMonth	zidz(manHrsNeeded,remainingTime.average())	Task / (Person * time)
DE20	impacts[CATEGORIES]	COO + MDK < 592? MDCAT1(sumconsts[CATEGORIES]) :MDCAT1(sumconsts[CATEGORIES]) /1.5	Task/time
DE21	MDtoImpactRate[CATEGORIES]	LPSF_S <= 100? MD[CATEGORIES]*percentageOFnegativeMD[CATEGORIES]: MD[CATEGORIES]*percentageOFnegativeMD[CATEGORIES]	Task/time
DE22	percentageOFnegativeMD	MDK<1? 0.9: 0.5	1/time
DE23	innovativeMD[CATEGORIES]	MD[CATEGORIES]*(1- percentageOFnegativeMD[CATEGORIES])	Task/time
DE24	completionFraction[SUBSTAGES]	zidz(finishedWork[SUBSTAGES],WIP_value[SUBSTAGES])	unitless
DE25	projectIsDone[SUBSTAGES]	completionFraction[SUBSTAGES]>=1?1:0	unitless

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		$\text{projectIsDone}[\text{SUBSTAGES}] \neq 0 \ \&\&$	
		$\text{WIP}[\text{SUBSTAGES}] < 0 \ ? \ 0 :$	
DE26	$\text{requiredWorkflow}[\text{SUBSTAGES}]$	$\max(\text{xidz}(\text{WIP}[\text{SUBSTAGES}], \text{remainingTime}[\text{SUBSTAGES}], \text{maxWorkflow}[\text{SUBSTAGES}]), \text{maxWorkflow}[\text{SUBSTAGES}])$	Task/time
DE27	$\text{remainingTime}[\text{SUBSTAGES}]$	$\max(0, \text{completionDate}[\text{SUBSTAGES}] - \text{time}())$	time
DE28	$\text{completionRate}[\text{SUBSTAGES}]$	$\text{projectIsDone}[\text{SUBSTAGES}] == 1 \ ? 0 :$ $\text{delay}(\min(\text{requiredWorkflow}[\text{SUBSTAGES}], \text{prod}[\text{SUBSTAGES}] \cdot \text{resourcesProductivityPerSS}[\text{SUBSTAGES}]), \text{startMonth}[\text{SUBSTAGES}])$	Task/time
DE29	$\text{timeToDiscoverMDs}[\text{SUBSTAGES}]$	$\text{effectOfSchedulePressureOnConstraintsRemoval}(\text{completionFraction}[\text{SUBSTAGES}])$	time
DE30	$\text{MD_IncidentsRate}[\text{CATEGORIES}]$	$(0.061 \cdot \text{MD}[\text{CAT1}] + 0.04 \cdot \text{MD}[\text{CAT4}]) / \text{timeToDiscoverMDs}[\text{SS1}]$	Task/time
DE31	$\text{MD_IncidentsRate}[\text{SUBSTAGES}]$	$\text{MD}[\text{CATEGORIES}] / \text{timeToDiscoverMDs}[\text{SUBSTAGES}]$	Task/time
DE32	$\text{resourcesComing}[\text{RESOURCES}]$	$\text{resourcesGap}[\text{RESOURCES}] > \text{TOT_Resources}[\text{RESOURCES}]?$ $(\text{resourcesGap}[\text{RESOURCES}] - \text{TOT_Resources}[\text{RESOURCES}]) / \text{TimeToIncreaseWorkforce}$	Person/time
DE33	$\text{crowdingEffectOnConstructionEfficiency}[\text{RESOURCES}]$	$\text{xidz}(\text{requiredResources}[\text{RESOURCES}], \text{resources}[\text{RESOURCES}])$	time
DE34	$\text{resources}[\text{RESOURCES}]$	$\text{changeInResources}[\text{RESOURCES}] - \text{dismissals}[\text{RESOURCES}] \cdot \text{xidz}(\text{resources}[\text{RESOURCES}], \text{TOT_Resources}[\text{RESOURCES}])$	Person

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DE35	resourcesEfficiency [RESOURCES]	crowdingEffectOnConstructionEfficiency[RESOURCES]*BIMEffectOnCommunication*plannedProductivity *LPSEffectOnEfficiency	Person
DE36	Refficiency_To_SS[SUBSTAGES]	Regression Equation	Person
DE37	plannedProductivity	uniform_discr(20,40)	Person
DE38	TOT_Resources [RESOURCES]	resources[RESOURCES]+newWorkForce[RESOURCES]	Person
DE39	dismissals [RESOURCES]	resourcesGap[RESOURCES] < TOT_[RESOURCES] ? (TOT_Resources[RESOURCES] - resourcesGap[RESOURCES])/ dismissalTime[RESOURCES] : 0 remainingTime[SUBSTAGES] <= 0 && !(projectIsDone[SUBSTAGES] != 0) ?	Person/time
DE40	schedulePressure[SUBSTAGES]	maxSchedulePressure : zidz(requiredWorkflow[SUBSTAGES], normalWorkFlow[SUBSTAGES])	unitless
DE41	normalWorkFlow [SUBSTAGES]	RG_TO_SS[SUBSTAGES]*normalProductivity	Task/time
DE42	overtime [SUBSTAGES]	overtimeTBFTN(schedulePressure[SUBSTAGES])	time
DE43	effFatigueProductivity [SUBSTAGES] =	fatigueEffProductivityTBFN(averageOvertime[SUBSTAGES]) effFatigueProductivity[SUBSTAGES]* normalProductivity	1/time
DE44	prod [SUBSTAGES]	* overtime[SUBSTAGES]* impactOfWorkSpaceLimitation[SUBSTAGES]+(M DSS[SUBSTAGES])	Task / (time * Person)
DE45	workspacePerCrewAvailable[SUBSTAGES]	workspaceAvailable*resourcesProductivityPerSS[SUBSTAGES]	Person * space
DE46	impactOfWorkSpaceLimitation	impactOfWorkSpaceLimitations(workspacePerCrewAvailable[SUBSTAGES])	

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DE47	changeInLocations	completionFraction.average() locationsDesign >0 ? 1 : 0	<1	&&	space/time
DE48	uncompensableDelays	projectDuration*0.85 completionFraction.average() 0.80 ?abs(projectDuration - time()) : 0 averageOvertime.average()>1? newWorkForce.average()*	<=	time() &&	time
DE49	constructionResources Cost	constructionResourceUnitCostPercentage averageOvertime.average()*overtimeUnitCost: newWorkForce.average() constructionResourceUnitCostPercentage	*	*	R\$/time
DE50	constructionResourceU nitCostPercentage	7.5			1/ (Person * time)
DE51	overtimeUnitCost	1.2			\$/time
DE52	WIP[SUBSTAGES]	MD_IncidentsRate[SUBSTAGES] completionRate[SUBSTAGES] constraintsRate[Constraints] LPSF_S + BIMF_S >=50 ?	-	+	Task
DE53	wasteRate[SUBSTAGE S]	wasteGenerationRate(completionFraction[SUBST AGES]) *completionRate[SUBSTAGES]*0.7 : wasteGenerationRate(completionFraction[SUBST AGES])			Task/time
DE54	replanningRate[CONST RAINTS]	zidz(Waste[IMPACTS], timetoDetectConstraints[CONSTRAINTS])			Task/time
DE55	d(Waste[IMPACTS])/dt	MDtoImpactRate[CATEGORIES]+wasteRate[SUB STAGES]-replanningRate[CONSTRAINTS]			Task
DE56	spaceChange	zidz(durationInHrs *resourcesGap.average() ,finishedWork.average()) occupiedLocations *spaceChange		>=	1/time
DE57	locationsUtilisationRate	initialLocations :occupiedLocations *spaceChange	?	0	space/time

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DE58	workspaceAvailable	initialLocations-finishedLocations-occupiedLocations		space
DE59	initialLocations	50		space
		LPSF_S	>= 50 ?	
DE60	LPSEffectOnEfficiency	1.5*impactOfCommitementPlanning 1*impactOfCommitementPlanning indirectCost	:	unitless
DE61	projectCost	zidz(uncompensableDelaysCost,uncompensableDelays)* time() +		\$
DE62	uncompensableDelays Cost	1.25		\$
DE63	indirectCost	indirectCostPrecentage * Waste.average()		\$
DE64	indirectCostPrecentage	0.6		\$/ Task
DE65	impactOfCommitement Planning	COO>=50? 1.5: 1		unitless
DE66	MDSS[SUBSTAGE]	MDSS_SUBSTAGE(innovativeMD.average()) LPSF_S <=60? zidz(constraints[CONSTRAINTS], timetodetectConstraints[CONSTRAINTS]):		Task
DE67	constraintsRate[CONSTRAINTS]	zidz(zidz(constraints[CONSTRAINTS] , timetodetectConstraints[CONSTRAINTS]), impactOfCOOonConstraints ImpactofLPonConstraints(LPSF_S)) projectIsDone[SUBSTAGES] ==1 ?0 :		Task/time
DE68	completionRate	delay(min(requiredWorkflow[SUBSTAGES] prod[SUBSTAGES] *resourcesProductivityPerSS[SUBSTAGES]),start Month[SUBSTAGES]) resourcesComing[RESOURCES] changeInResources[RESOURCES]		Task/time
DE69	d(newWorkForce [RESOURCES])/dt	- dismissals[RESOURCES] zidz(newWorkForce[RESOURCES], TOT_Resources[RESOURCES])	*	Person

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DE70	changeInResources [RESOURCES]	newWorkForce[RESOURCES]/resourceAdjustmentTime	Person/time
DE71	resourceAdjustmentTime	2	time
		LPSF_S ≤ 100?	
DE72	MDtoImpactRate [CATEGORIES]	MD[CATEGORIES]*percentageOfNegativeMD[CATEGORIES]: MD[CATEGORIES]*percentageOfNegativeMD[CATEGORIES]	Task/time

IV.4. Table Functions

Table IV-4 presents the table functions, preset non-linear functions that are not mathematical and represent relationships between different variables; some of these tables are observed from collected data and literature.

Table IV-4 – Table functions in D3M

	Table Function	Data	Unit
T1	effectOfSchedulePressure OnConstraintsRemoval	{(0, 5), (0.1, 4.5), (0.2, 4), (0.3, 3), (0.4, 2), (0.5, 1), (0.6, 0.9), (0.7, 0.8), (0.8, 0.7), (0.9, 0.6), (1, 0.5)}	time
T2	resourcesAllocationTBFT N	{(0, 1), (0.5, 0.8), (0.8, 0.2), (1, 0)}	unitless
T3	MDCAT1	{(0, 0), (1, 0.5), (2, 5), (5, 12), (10, 13), (15, 14), (30, 15)}	Task/time
T4	MDCAT2	{(0, 0), (10, 20), (20, 50), (30, 100), (40, 110), (50, 115), (60, 120), (70, 125), (80, 130), (90, 135), (100, 140)}	Task/time
T5	MDCAT3	{(0, 0), (5, 3), (20, 5), (30, 8), (40, 9), (50, 10), (60, 15), (70, 17)}	Task/time
T6	MDCAT4	{(0, 0), (2, 3), (3, 30), (4, 35), (5, 40), (6, 61.5), (9, 62), (11, 63), (15, 64)}	Task/time

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T7	MDCAT5	{(0 , 0),(3 , 4),(8 , 6) , (25 , 8) , (35 , 12) , (45,20) , (50,21) , (60 , 21.5) , (70 , 22) , (80 , 22.5) , (90 , 23) }	Task/time
T8	overtimeTBFTN	{(0 , 0.7),(1 , 1),(1.2 , 1.2) , (1.5 , 1.4),(2 , 1.45) , (5,1.5) , (10,1.55) , (20 , 1.6) }	time
T9	fatigueEffProductivityTB FN	{(0 , 1),(0.1 , 0.95),(0.2 , 0.9) , (0.3 , 0.87),(0.4 , 0.83) , (0.5,0.8) , (0.6,0.75) , (0.7 , 0.7) , (0.8 , 0.68) , (0.9 , 0.65) , (1 , 0.6) }	1/time
T11	impactOfApplyingBIMT echnology	{(0 , 0.1),(0.5 , 0.15),(1 , 0.35) , (1.5 , 0.55),(2 , 0.725) , (2.5,1.1) , (3,1.5) , (3.5 , 2.025) , (4 , 2.825) , (4.5 , 3.7) , (5 , 5) }	unitless
T12	wasteGenerationRate	{(0 , 0.05),(0.1 , 0.09),(0.2 , 0.25) , (0.3 , 0.4),(0.4 , 0.45) , (0.5,0.55) , (0.6,0.65) , (0.7 , 0.55) , (0.8 , 0.45) , (0.9 , 0.35) , (1 , 0.2) }	unitless
T13	schedulePressureEffectT BFTN	{(0 , 0.4),(0.25 , 0.5),(0.5 , 0.6) , (0.75 , 0.8),(1 , 0.9) , (1.25,1) , (1.5,1.2) , (1.75 , 0.9) , (2 , 0.6) , (0.9 , 0.35) , (1 , 0.2) }	unitless
T14	impactOfWorkSpaceLimi tations	{(5 , 0.65),(10 , 0.68),(15 , 0.7) , (20 , 0.76),(25 , 0.8) , (30,0.93) , (35,0.95) , (40 , 0.97) , (45 , 0.98) , (50 , 0.99) }	unitless
T15	timeToDiscoverWaste	{(0 , 5),(0.1 , 4.5),(0.2 , 4) , (0.3 , 3),(0.4 , 2) , (0.5,1) , (0.6,0.9) , (0.7 , 0.8) , (0.8 , 0.7) , (0.9 , 0.6) , (1 , 0.5) }	time
T16	ImpactofLPsonConstrain ts	{(0 , 0),(20 , 0.1),(40 , 0.22) , (50 , 0.5),(60 , 0.75) , (100,0.88) , (140,0.91) , (180 , 0.94) , (200 , 0.96) , (250 , 0.98) , (260 , 0.99) }	unitless
T17	ImpactOfLPsonWasteRe duction	{(0 , 0.05),(20 , 0.09),(40 , 0.25) , (50 , 0.4),(60 , 0.45) , (100,0.55) , (140,0.65) , (150 , 0.75) , (160 , 0.8) , (170 , 0.9) }	unitless

T18	MDSS1	$\{(1, 0.04685), (2, 0.12186118), (5, 0.23425), (10, 0.4685), (15, 0.70275)\}$	Task/time
T19	MDSS2	$\{(1, 0.14344), (2, 0.37309476), (5, 0.7172), (10, 1.4344), (15, 2.1516)\}$	Task/time
T20	MDSS3	$\{(1, 0.33001), (2, 0.85805652), (5, 1.65005), (10, 3.3001), (15, 4.95015)\}$	Task/time
T21	MDSS4	$\{(1, 0.06306), (2, 0.1640118), (5, 0.3153), (10, 0.6306), (15, 0.9459)\}$	Task/time
T22	MDSS5	$\{(1, 0.09973), (2, 0.2593535), (5, 0.49865), (10, 0.9973), (15, 1.49595)\}$	Task/time
T23	MDSS6	$\{(1, 0.062061), (2, 0.16138018), (5, 0.310305), (10, 0.62061), (15, 0.930915)\}$	Task/time
T24	MDSS7	$\{(1, 0.06463), (2, 0.16815084), (5, 0.32315), (10, 0.6463), (15, 0.96945)\}$	Task/time
T25	MDSS8	$\{(1, 0.01873), (2, 0.0487316), (5, 0.09365), (10, 0.1873), (15, 0.28095)\}$	Task/time
T26	MDSS9	$\{(1, 0.25275), (2, 0.65722892), (5, 1.26375), (10, 2.5275), (15, 3.79125)\}$	Task/time
T27	MDSS10	$\{(1, 0.22201), (2, 0.5774409), (5, 1.11005), (10, 2.2201), (15, 3.33015)\}$	Task/time
T28	MDSS11	$\{(1, 0.07174), (2, 0.18663684), (5, 0.3587), (10, 0.7174), (15, 1.0761)\}$	Task/time
