Karaz, M. & Texiera, J.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

A SYSTEM DYNAMIC MODELLING APPROACH FOR INTEGRATED LEAN-BIM PLANNING AND CONTROL METHODS

Mahmoud Karaz[1] and José Manuel Cardoso Teixeira[2]

ABSTRACT

Traditional planning and control methods do not accurately reflect the construction reality and lack feedback loops. The Last Planner System (LPS) and Location-based Management System (LBMS) have been suggested as socio-technical systems to generate practical and actionable real-life data based on production theories and logic. This data can be effectively communicated, analysed, and managed using the capabilities offered by Building Information Modelling (BIM) workflows. However, a true integration between Lean Construction-BIM is not yet matured, where parallel use of both concepts is still more common. This paper presents a conceptual framework based on a system dynamic modelling approach to elaborate a causal loop diagram (CLD). The CLD explores the interactions between basic management functions and waste, on this basis this paper proposes how the integration between LPS, LBMS, and BIM can be harnessed to apply waste elimination strategies. The results of this study can be applied as lean policy analysis for new lean adaptors to understand the impact of Lean-BIM for planning and controlling various wastes across the construction supply chain.

KEYWORDS

Last Planner System, Location-Based-Management, System Dynamics, Casual Loop Diagram, Building Information Modelling, Construction Waste

INTRODUCTION

The construction industry is highly fragmented, has low productivity, and is a slow adopter of new techs. Most construction projects are waste-prone, resulting in delays, defective products, accidents, material waste and cost overruns. The production is traditionally managed, which relies on ad hoc decisions directing site activities with low-resolution and unreliable plans without channels for feedback from downstream players, therefore encapsulating production tasks in black boxes (Sacks et al., 2018). That challenges the construction stakeholders to extract useful and reliable information on a weekly and daily basis about the production.

About 54% of root causes of project delays and poor productivity are attributed to unreliable planning and control Ballard & Howell (1998). In Koskela's (1992, 2000) theory of the Transformation-Flow-Value (TFV), it is explained that these inefficiencies are attributed to the Transformation (T) view because it hides the propagated waste across the construction supply chain and ignores the value chain between project actors and the final customer hence suggesting the Flow (F) and the Value (V) views to complement the T view. The Flow (F) view is an essential concept in lean philosophy that decomposes the construction processes into

[1] PhD Student, Department of Civil Engineering, University of Minho, School of Engineering, Guimarães, Portugal, mahmoud.karaz@outlook.com. The Centre for Territory, Environment and Construction (CTAC).

[2] Associate Professor, Department of Civil Engineering, University of Minho, School of Engineering, Guimarães. The Centre for Territory, Environment and Construction (CTAC).

Value-Added (VA) and Non-Value-Added (NVA) activities (i.e., work-in-progress, rework, defects, unfinished products, and waiting) (ibid). At the same time, the Value perspective stresses the importance of actively pulling requirements from the final and internal customers to avoid non-value activities.

A practical implementation of the F is planning and control systems, namely, Last Planner System (LPS) and Location-Based Management (LBMS). LPS is a socio-technical system that increases the planning resolution collaboratively to shield downstream from the upstream variability (Ballard, 2000). LBMS is a technical Flow-based method that calculates forecasts, production rates, quantities, and resource consumption for each task and trade according to their physical location (Kenley & Seppänen, 2010). Both systems complement each other in attempting to bring the production problems to the surface by targeting continuous, reliable, and one-piece flow (Seppänen et al., 2010). The combination of both systems could establish production planning that addresses bottlenecks through structuring, sequencing, managing handoffs, and visualising the construction flow, and proactive control that aims at identifying, analysing and removing constraints while alerting people about potential interference in the production system (Seppänen et al., 2015). That would increase production flexibility and credibility through detailed, measurable, reliable, and stable plans (Frandson et al., 2014).

Construction production is information intensive, and planning accuracy requires consistent information models which can be accessed across organisation boundaries. Building Information Modelling (BIM) is a visual, computational, and analytical process that enhances the communication of integrated production information (process and product) (Dave & Sacks, 2020). According to the LC-BIM matrix provided by Sacks et al. (2010), 56 positive interactions could support value and waste elimination concepts. The application of LPS becomes potent by incorporating automated BIM workflows where decisions and feedbacks rely on information streamlined from BIM models during performing constraint analysis, task definition, sizing, and sequencing (Gerber et al., 2010). The development of software as a service and tools based on LPS-BIM is growing as an independent research area; examples of provided prototypes are KanBIM (Sacks et al., 2010), VisiLean (Dave, 2013), LPS-based BIM (Heigermoser et al., 2019), and Beam! (Schimanski et al., 2021). The application of LBMS requires BIM workflows to perform and manage extensive calculations of quantities, durations, resource consumption and production rate (Kenley & Seppänen, 2010). A commercial example of this integration is presented in Vico software which automates LBMS logic using BIM functionalities and extends 4D logic from CPM to LBMS (Trimble, nd).

Conversely, the current BIM solutions did not fully integrate LPS and LBMS functions. Instead, they are performed in parallel, which misses the full potential of both planning and control systems. Also, no research discussed construction waste explicitly using the three concepts. Therefore, this paper provides Casual Loop Diagram (CLD) to illustrate the waste propagation across a construction production system based on the work of Formoso et al. (2015, 2020) and then proposes a conceptual framework that applies LPS, LBMS and BIM to tackle the construction wastes. The first two steps of the SDM method are to define the research problem and conceptualise this problem using CLDs, which will be the focus of this paper.

The subsequent sections are structured as follows: a brief literature review on construction wastes, an explanation of LPS and LBMS, and a discussion of the existing BIM functionalities for planning and control purposes. The next section presents CLD for waste networks combined with functional areas of lean-BIM for planning and control. The final sections discuss the research contributions and conclude this paper's major elements.

LITERATURE REVIEW

CONSTRUCTION WASTE

Construction waste is a high-level concept that hinders productivity and incurs capital loss which is challenging to measure systematically (Formoso et al., 2020; Viana et al., 2012)—causing massive negative impacts on environmental, economic, and social dimensions. According to Horman and Kenley's (2005) meta-analysis, 49.6% of construction operations are NVA (Non-Value Adding) activities. The literature has approached construction waste using various definitions, including rework (Love and Li 2000), product defects (Josephson and Hammarlund 1999), re-entrant flow (Sacks et al. 2017), transportation (Belayutham, González and Yiu, 2016), and institutional waste (Sarhan et al. 2017). This disparity in waste measures shows that it is challenging to formulate a holistic framework and attempt to complete an analysis of the root causes of construction waste (Formoso, Bølviken, and Viana 2020).

The construction waste propagates in complex networks. Those cycles can be modelled using causal loops that relate wastes in unidirectional and bidirectional ways. The propagation of waste cycles inherits the same properties of construction processes (i.e., pooled, sequential, or reciprocal) (Koskela et al., 2013). Also, waste can be understood as discrete (task-level), synergistic (project-level) and systematic (organisational and contractual level) (Fernández-Solís & Rybkowski, 2012). Formoso et al. (2020) categorised the construction waste into previous stages (design, planning and control, material supply, and training); production wastes (quality deviation, making-do, transportation, waiting, work-in-progress; inventories), and terminal waste or traditional waste metrics (rework, defects, material waste, safety issues, gas emissions). The literature shows various similarities in taxonomies of production waste, but it is difficult to grasp their applicability without a series of case studies to provide a holistic view.

THE LAST PLANNER SYSTEM© (LPS)

The LPS is the most applied from LC methods; sometimes, the LPS term is used interchangeably with LC. The key goal of LPS is to shield downstream from the upstream variability to increase planning reliability and workflow stability (Ballard, 2000). The second feature is providing commitment planning which focuses on facilitating conversation between planners to identify activities, their sizes, sequence, and related constraints. The third feature is to increase planning details based on Kanban planning; LPS breaks down the construction planning into four to five stages, namely master planning, phase planning, look-ahead planning, weekly planning, and learning, as illustrated in Figure 1. LPS uses social-technical measures that steer people to communicate project activities in detail with their constraints and requirements. Through a higher level of planning detail, planners can filter and pull ready (non-constraint) activities from the collaboratively developed backlog. The control function of LPS is enabled through PPC (Plan Percent Complete) and RNC (Reasons for non-compliance) metrics. They can be used to track the construction's progress and constraints to production—examples of analysis methods that can be used are 5whys and A3.

	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	• Define key milestones • Identify critical path (CPM) • Assign start-finish relations	• Apply reverse planning • Identify handoffs, durations, and overlaps • Define 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) • Unfinished 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 1: The structure of LPS stages, related activities, addressed wastes and actors.

LOCATION-BASED MANAGEMENT (LBMS)

LBMS is a system of preplanning, planning, scheduling, and controlling production according to units of physical locations. That is based on locations by calculating the quantity of work to be accomplished and the production rate (Kenley & Seppänen, 2010). LBMS breaks down the project into Location Based Structure (LBS), using the same Work Breakdown Structure (WBS) logic but applied to physical locations (Kenley & Seppänen, 2010). LBS divides the project into interdependent structures that can be built separately and narrowed to manageable locations where one trade can operate continuously without waiting. According to LBMS logic, reducing the interdependencies provided by CPM, removing float between tasks, and synchronising production rates is possible. The control indicators applied in LBMS can forecast production capabilities and provide information about the root causes of cascading delay (i.e., work-in-progress, waiting, rework, and congestion) (Kenley & Seppänen, 2010). LBMS reduces production complexity by streamlining continuous flow across location, which steers planning targets towards stable and interrupted production, gives clear directions for trade crews, and reduce trade risk and waiting time (Biotto & Kagioglou, 2020).

REFLECTION ON LPS AND LBMS

Although the wide acceptance of LPS, many gaps have been reported regarding PPC metrics, automation level, and cost management. Firstly, PPC does not measure or reflect any flow parameters, such as variation in production rates, trade discontinuities, out-of-sequence work, product CTs, WIP levels, bottleneck production rates, and levels of non-value-adding work (Maraqa et al., 2021). That can be partially addressed using LBMS, which provides metrics of flow quality, and actual flow line charts, which show the locations, and the movement of trade crews across spatial-temporal dimensions (Maraqa et al., 2021). However, focusing on productivity metrics offered by LPS and LBMS can lead to counterproductive behaviour by steering the production towards results instead of managing by means. Secondly, a major gap shows that LPS and LBMS are still lagging in supporting real-time flow monitoring, which is a challenging lack of automation, as Ratajczak et al. (2017) indicated. Thus, adopting more tracking and tracing technologies, such as IoT sensors, is envisioned for autonomous data entry for BIM-based production planning and control systems (Dave et al., 2016). Regarding the cost management function, there is little evidence of cost control supported by LPS (Schimanski et al., 2021), which can be complemented by the measures supplied by LBMS in calculating quantities, resource consumption and production rates.

BUILDING INFORMATION MODELLING

BIM becomes a de facto technology in AECO industries which brings various actors to use a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions (ISO, 2018). BIM functionalities can overcome major information problems such as design inconsistency, errors, and duplications caused by conventional design workflows (Sacks et al., 2018). Successful implementation of BIM stands on three pillars, process, people, and technology (Hardin & McCool, 2015). Lean construction can complement the former two pillars, while the latter relies solely on extensions to the existing BIM functionalities. These functionalities include parametric modelling, interoperability, clash detection, 4D simulation, functional analysis, and documentation (Sacks et al., 2018). Thanks to interoperability functionality, it is possible to seamlessly exchange design information between different BIM systems and design speciality (e.g., by Industry Foundation Classes (IFC)) (Sacks et al., 2018). 4D planning encourages discussion of several plan alternatives, increases process transparency, and improves planning reliability (Bortolini et al., 2019).

However, 4D planning is not fully exploited in production planning (Schimanski et al., 2021) because short-term planning is not considered in commercial 4D planning (Ardila & Francis, 2020), which is mainly programmed for documenting and analysing production plans according to activity-based logic. Thus, most BIM solutions are not fully developed for lean data processing; instead, they are used in parallel with LPS and LBMS (Schimanski et al., 2021). Therefore, lean planning and control systems and BIM integration exist, but their full potential is not realised yet.

RESEARCH METHODOLOGY

This study aims to enable lean stakeholders to identify the effect of LPS, LBMS and BIM on waste elimination by micro-mapping objects and spaces using the Casual Loop Diagram (CLD) according to the theory of System Dynamic Modelling (SDM). The SDM measures the effect of change in a system over time with a high level of abstraction and minimum level of detailing. SDM was coined in the 1950s by Jay Forrester to depict the change in socio-economic systems' behaviour over time as a broad evolving methodology to conceptualise, describe, analyse, and manage feedback systems (Sterman, 2002).

Figure 2 illustrates the research methodology used in this paper, representing four steps of developing SDM. The scope of this paper is to conceptualise the problem (step 1) by formulating a Casual Loop Diagram (CLD) for production wastes and construction management functions (including material delivery, production planning and control, site layout planning, and product design using BIM). CLD can explain the dynamic hypothesis by visualising a complex system's cause-and-effect relationships between variables. Constructing a CLD involves six activities 1) research question definition, 2) variables identification, 3) links between variables, 4) polarity identification, 5) assigning feedback loops, and 6) determining delays (not included in this paper). The main use of CLDs is communicating with stakeholders and constituting a framework that captures expert knowledge, and a main drawback of SDM is that a high level of abstraction works with averages that cannot be used at operational and tactical levels. Also, it has limited animation capabilities compared with Agent-Based Modelling (ABM) and Discrete Event Simulation (DES).

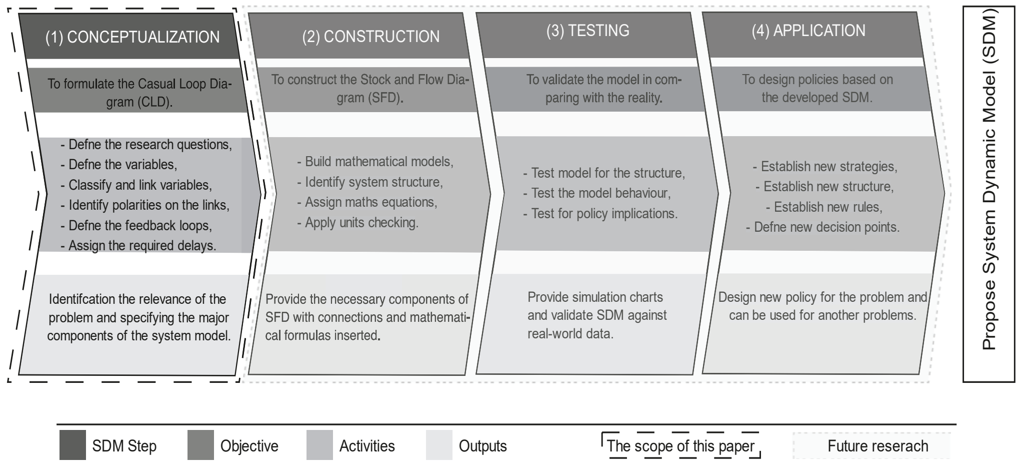

Figure 2: The research methodology

CAUSAL LOOP DIAGRAM (CLD) FOR WASTE ELIMINATION

CLD is a conceptual tool that shows dynamic and complex problems related to their solutions and reveals a chain of cause and effect. Such a diagram consists of a set of nodes representing variables connected, the relationship between these variables, represented by arrows, can be labelled at the arrowhead as either positive or negative. The CLD presented in 3 is based on (Formoso et al., 2015, 2020), who proposed a network analysis that could depict the patterns of the construction wastes by drawing links among taxonomies of wastes and between the construction waste and the production system stages. This CLD also adopts the components of Integrated Lean Project Delivery (ILPD) presented by (Ballard & Howell, 2003), lean design, lean supply, lean production planning and control. In addition, BIM processes and Quality management were added to the CLD to investigate the relationships between all mentioned concepts and production waste concepts. By analysing the diagram of Figures 3, the following loops can be clearly recognized:

Loop R1 highlights the effect of material delivery and site layout planning on the inventory, where inventory is a temporary facility that should be planned in the site layout. The more frequently delivered materials, the bigger inventory on site is needed when the resource consumption may not meet the delivery rate. Additionally, the more parts are delivered, 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 arising from Production Planning and Control (PP&C), for instance, improper allocation of materials, poor site layout plans, damage during transportation (as shown in Loop R4), poor handling, and improper material staging and among others (For more about material waste, check (Formoso et al., 2002). In loops B1 and R3, the labour movement across physical locations is affected by the material delivery, the routes and site layout design and planned activities by Production Planning and Control (PP&C). Information about labour routes across the physical locations can be scheduled and controlled through LBMS with the support of BIM for obtaining quantities and geometrical analysis for 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, etc. 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. As well as, PP&C has to 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, as well as this variable limit the likelihood of making-do 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 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, by inserting measures of PP&C associated with planned site layout planning (SLP) (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 perquisite materials, a making-do waste arises, which is responsible for other wastes such as Work-In-Progress (WIP) and unfinished works and hinders labours' productivity. Another waste not communicated in Figure is substitution waste, a phenomenon that urges to substitute unavailable materials with other materials to meet schedule 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 be snowballed 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 (Sacks et al., 2018), 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. A true 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 is not presented yet. However, the potentials of BIM functionalities' impact on waste reduction are evident even on final wastes such as rework, material waste, and capital waste.

B3, R9, and R10 concern the quality management to control variability using quality control charts and continuous improvement methodology based on the PDCA cycle (Deming, 1982). Construction variability is the main source of product defects and process discontinuity, leading to reworks, poor productivity, and eventually to, capital waste and cascading delays. Loop R7 illustrate 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 easiest 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. Eventually, this phenomenon led to interruptions in workflow and interference with other trades' schedules, leaving labours 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.

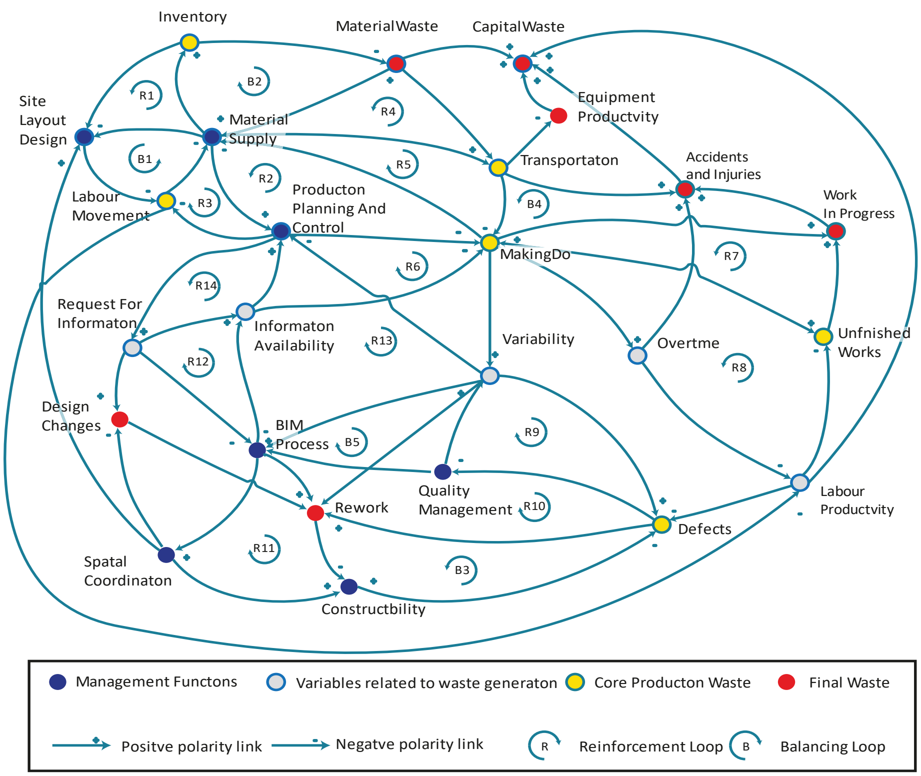

Figure 3: A CLD of wastes and production system functions adapted from (Formoso et al., 2020)

BIM-BASED INTEGRATED PLANNING AND CONTROL

BIM workflow is in the middle of the proposed framework in Figure 4 because BIM is considered as single truth source and because it supplies the necessary data for the variables governing LPS and LBMS (i.e., start and finish time, production data, geometry, and resource quantities). LPS can apply different scheduling methods, but this research applies LBMS forecasts for scheduling, planning, and controlling the production and alarms LPS stakeholders about upcoming and ongoing production problems, and supplies them with locations, crews' consumption (manhour/unit), production rates, and quantities (Kenley & Seppänen, 2010). While the site teams' feedback suppliy information about quantities, constraints and commitments during look-ahead planning and weekly planning (Seppänen et al., 2015). Thus, the deficiencies of LPS will be complemented using LBMS countermeasures (Tommelein & Emdanat, 2022).

During the master scheduling stage, milestones are determined, and the master schedule is defined using LBMS scheduling techniques. BIM is at schematic design, which approximates estimations, identifies main phases and primitive tasks, and provides geometrical analysis for defining a rough Location Based Structure (LBS). The outputs are milestones, phases, flow line schedule and Gant chart schedule. In this stage, high-level waste elimination can be targeted (i.e., capital waste, environmental waste, safety issues, rework and defect rates, and inventory). In phase scheduling, collaborative backwards (pull) planning from defined milestones in the master schedule is applied, where work chunks and handoffs can be determined without defining durations. LBMS functions are divided into scheduling and optimisation (Seppänen et al., 2010). The first targets the setting of LBS (i.e., units of equal size of work in locations that assures trades to work until they get work completed in a location before moving to another location). Collaboratively, LBMS also seeks optimisations in phase scheduling (including adding more resources, splitting tasks, accepting discontinuous work, decreasing crew size, and adding more scope) (Seppänen et al., 2015). The spatial coordination stage of BIM can provide 4D schedules for better visualisation and clash detection to identify the product systems interference. The aimed waste in phase scheduling are design changes, reduction of Request for Information (RFI), schedule overrun, movement, transportation, and defects.

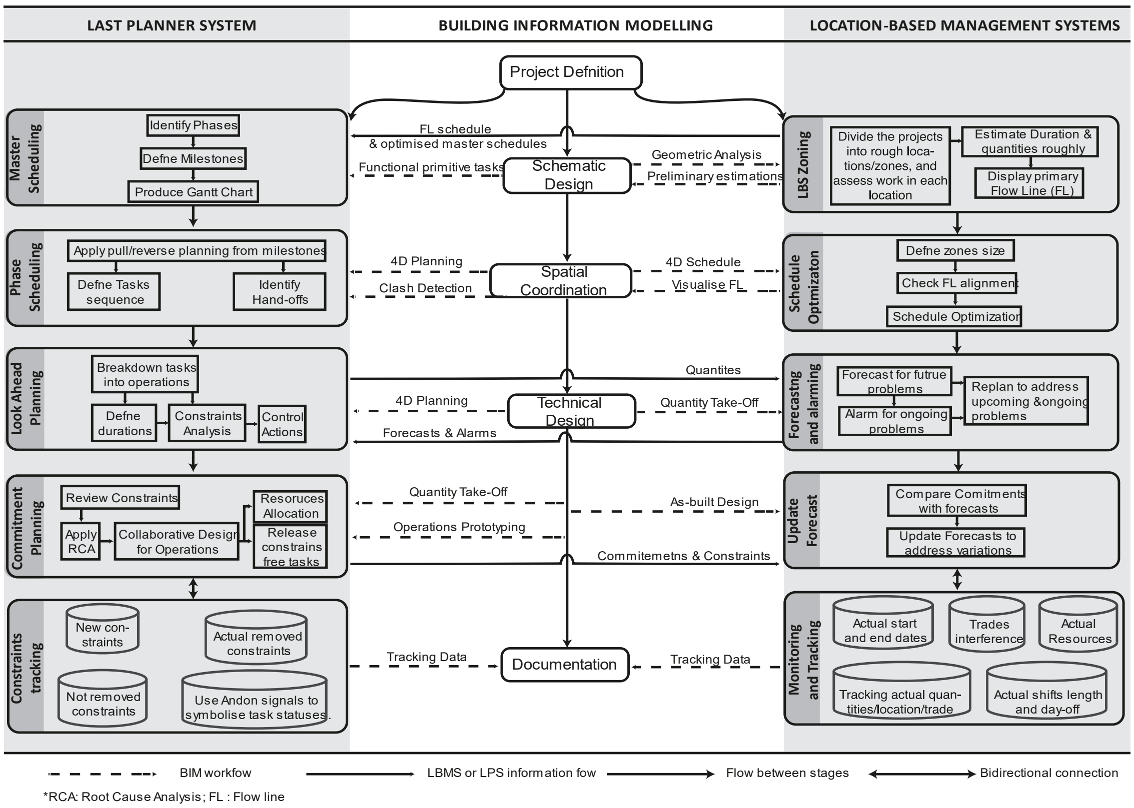

Figure 4: Assembled sub-systems of LPS, LBMS, and BIM.

The control functions commence with the look-ahead planning stage. A social process of LPS breaks operations into tasks, and a technical process of LBMS breaks operations into locations. In LPS, stakeholders apply constraint analysis to identify, diagnose, assign, and remove potential constraints for each task in a phase when durations are determined for each task. LBMS collects the required data about crew consumption, quantities, and production rates from trades, BIM take-off, and LPS. This information is used to forecast future problems and alarm ongoing production problems. Root Cause Analysis (RCA) is applied to seek systematic control actions that remove constraints supplied by LPS and mitigate the schedule risk provided by LBMS.

In the commitment planning stage, the LPS teams review the constraints and commitments in short-term windows. A collaborative effort is applied to design for operations, and the simulation functionality in BIM would be useful for providing prototyping at the operational level (Seppänen et al., 2015). At this stage, LPS functions are more applied than LBMS, but the LPS commitments are to be compared with LBMS forecasts to adjust exceeded plans (Seppänen et al., 2010). Finally, Production tracking is necessary to pull information from the site to planning and control systems, as shown in Figure . This function can detect the status of commitments, constraints, tasks progress, bottlenecks information, interference, actual resources, start and finish dates, shifts, and other quantities. The literature suggested various technologies to track and monitor the production information (e.g., (Dave & Sacks, 2020; Zhang et al., 2015). Tracking and monitoring function is essential to close the feedback loop of the suggested system, increase the situational awareness of trades and planners about the production, and bring management attention towards critical issues that generate waste and hinder value delivery.

CONCLUSIONS

This paper applied the System Dynamics theory to investigate the impact of production planning, control, and BIM on waste elimination. Based on a literature review, a Causal Loop Diagram (CLD) was illustrated to highlight the dynamicity of waste propagation and the interactions and feedback loops among BIM and planning and control functions. Then a generic framework was proposed to assemble the flows between Location Based Management System (LBMS), Last Planner System (LPS), and BIM. Waste measures should be used as guidance and actionable language when applying LBMS and LPS-based BIM. LBMS and LPS provide systematic, preventive, and proactive waste elimination measures from the early stages of the project, while BIM provides enormous data collection, analysis, and exchange on the elaborated wastes. By harnessing BIM functionalities, lean practitioners could communicate potential production wastes at different planning and control stages.

System dynamics may be viewed as the initial methodology to analyse waste accumulation across a specific timeline. Thanks to the clarity a dynamic system model provides, stakeholders can identify and resolve planning and control issues and measure the impact of countermeasures on waste elimination efforts. The combination between the LPS and LBMS in association with BIM functionalities streamlines powerful improvement for the construction production systems. Regardless of the ease of understanding, CLDs can be communicated with stakeholders with diverse backgrounds and experiences. The proposed CLD requires additional concepts, such as delays which enhance the system behaviour by adding waiting time measures when necessary.

Moreover, the elaborated CLD is limited because it is abstract and conceptual, which may not build a reliable judgement to be implemented on a real-world project. This paper is part of ongoing research that aims to model lean thinking using system dynamics. The future research will collect experts' views based on the case study research method on the elaborated casual loops diagrams and transform them into operable stock and flow diagrams, which allows the researchers to simulate the system by manipulating the model's major variables and compare runs among the different scenarios across a specific timeline.

ACKNOWLEDGMENTS

This work is funded by National Funds through the FCT - Fundação para a Ciência e Tecnologia, I.P., under the scope of the project 2021.04751.BD.

REFERENCES

Ardila, F., & Francis, A. (2020). Spatiotemporal Planning of Construction Projects: A Literature Review and Assessment of the State of the Art. *Frontiers in Built Environment*, *6*, 128. https://doi.org/10.3389/FBUIL.2020.00128/BIBTEX

Ballard, G. (2000). The Last Planner System of Production Control [University of Birmingham, UK]. In *School of Civil Engineering - Faculty of Engineering: Vol. Doctor of philosophy*. https://doi.org/10.1017/CBO9781107415324.004

Ballard, G., & Howell, G. (1998). Shielding production: essential step in production control. *Journal of Construction Engineering and Management*, *124*(1), 11–17.

Ballard, G., & Howell, G. A. (2003). Lean project management. *Building Research and*

Information, *31*(2), 119–133. https://doi.org/10.1080/09613210301997
Biotto, C., & Kagioglou, M. (2020). Relating construction production design and planning activities with location-based scheduling techniques. In *Lean Construction: Core Concepts and New Frontiers* (p. 301). Routledge.
Bortolini, R., Formoso, C. T., & Viana, D. D. (2019). Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Automation in Construction*, *98*, 248–264. https://doi.org/10.1016/j.autcon.2018.11.031
Cheng, J.C.P., Won, J., Das, M., Cheng, J. C. P., Won, J., & Das, M. (2015). Construction and Demolition Waste Management using BIM technology. *23rd Ann. Conf. of the Int'l. Group for Lean Construction*, 159–160. www.iglc.net
Dave, B. (2013). Developing a Construction Management System Based on Lean Construction and Building Information Modelling. In *University of Salford*. University of Salford.
Dave, B., Kubler, S., Främling, K., & Koskela, L. (2016). Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in Construction*, *61*, 86–97. https://doi.org/10.1016/j.autcon.2015.10.009
Dave, B., & Sacks, R. (2020). Construction at the next nexus of Lean and BIM. In *Lean Construction: Core Concepts and New Frontiers* (pp. 54–84). Routledge.
Deming, W. E. (1982). *Out of the Crisis, reissue*. MIT press.
Fernández-Solís, J. L., & Rybkowski, Z. K. (2012). A Theory of Waste and Value. *International Journal of Construction Project Management*, *4*(2), 89–105. https://hdl.handle.net/1969.1/153692
Formoso, C. T., Bølviken, T., Rooke, J., & Koskela, L. (2015). A Conceptual Framework for the Prescriptive Causal Analysis of Construction Waste. *International Group for Lean Construction*, *July*, 454–462.
Formoso, C. T., Bølviken, T., & Viana, D. D. (2020). Understanding waste in construction. In P. Tzortzopoulos, M. Kagioglou, & L. Koskela (Eds.), *Lean Construction Core Concepts and New Frontiers* (pp. 129–145). Routledge.
Formoso, C. T., Soibelman, L., de Cesare, C., & Isatto, E. L. (2002). Material Waste in Building Industry: Main Causes and Prevention. *Journal of Construction Engineering and Management*, *128*(4), 316–325. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(316)
Frandson, A., Berghede, K., & Tommelein, I. D. (2014). Takt-Time Planning and the Last Planner. *Proceedings IGLC-22*, 571–580.
Gerber, D., Gerber, B., & Kunz, A. (2010). Building Information Modeling and Lean Construction: Technology, Methodology and Advances from Practice. *Proceedings IGLC*, 683–693.
Hardin, B., & McCool, D. (2015). *BIM and Construction Management* (2nd ed.).
Heigermoser, D., García de Soto, B., Abbott, E. L. S., & Chua, D. K. H. (2019). BIM-based Last Planner System tool for improving construction project management. *Automation in Construction*, *104*(June 2018), 246–254. https://doi.org/10.1016/j.autcon.2019.03.019
ISO. (2018). *ISO 19650-1:2018 - Organisation and digitisation of information about buildings and civil engineering works, including building information modelling (BIM) : Information management using building information modelling. Part 1, Concepts and principles*.
Kenley, R., & Seppänen, O. (2010). *Location-Based Management for Construction: Planning, scheduling and control* (1st Edition). Spon Press by Taylor & Francis.
Koskela, L. (1992). Application of the new production philosophy to construction. *Center for Integrated Facility Engineering*, 1–81. https://doi.org/Technical Report No. 72
Koskela, L. (2000). *An exploration towards a production theory and its application to*

construction [VTT Technical Research Centre of Finland].

Koskela, L., Bølviken, T., & Rooke, J. (2013). Which are the wastes of construction? *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, 905–914.

Maraqa, M. J., Sacks, R., & Spatari, S. (2021). Quantitative assessment of the impacts of BIM and lean on process and operations flow in construction projects. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-12-2020-1068

Ratajczak, J., Schimanski, C. P., Marcher, C., Riedl, M., & Matt, D. T. (2017). Mobile Application for Collaborative Scheduling and Monitoring of Construction Works According to Lean Construction Methods. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *10451 LNCS*, 207–214. https://doi.org/10.1007/978-3-319-66805-5_26

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM Handbook. In *BIM Handbook* (Third edit). John Wiley & Sons, Inc. https://doi.org/10.1002/9781119287568

Sacks, R., Korb, S., Barak, R., & Geva, G. (2018). *Building lean, building BIM: improving construction the Tidhar way* (Issue December 2017). Routledge Taylor & Francis Group.

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of lean and building information modeling in construction. *Journal of Construction Engineering and Management*, *136*(9), 968–980. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203

Sacks, R., Radosavljevic, M., & Barak, R. (2010). Requirements for building information modeling based lean production management systems for construction. *Automation in Construction*, *19*(5), 641–655. https://doi.org/10.1016/j.autcon.2010.02.010

Schimanski, C. P., Pasetti Monizza, G., Marcher, C., & Matt, D. T. (2021). Development of a BIM-based production planning and control system for Lean Construction through advancement and integration of existing management techniques. *Frontiers of Engineering Management*, *8*(3), 429–441. https://doi.org/10.1007/s42524-020-0105-5

Seppänen, O., Ballard, G., & Pesonen, S. (2010). The Combination of Last Planner System and Location-Based Management System. *Proceedings IGLC-18*, 467–476.

Seppänen, O., Modrich, R., & Ballard, G. (2015). Integration of Last Planner System and Location-Based Management System. *23rd Ann. Conf. of the Int'l. Group for Lean Construction*, 123–132.

Sterman, J. (2002). *System Dynamics: systems thinking and modeling for a complex world*.

Tommelein, I. D., & Emdanat, S. (2022). Takt Planning: An Enabler for Lean Construction. *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 866–877. https://doi.org/10.24928/2022/0198

Trimble. (n.d.). *Vico Software*.

Viana, D. D., Formoso, C. T., & Kalsaas, B. T. (2012). Waste in construction: A systematic literature review on empirical studies. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.

Zhang, S., Teizer, J., Pradhananga, N., & Eastman, C. M. (2015). Workforce location tracking to model, visualise and analyse workspace requirements in building information models for construction safety planning. *Automation in Construction*, *60*, 74–86. https://doi.org/10.1016/j.autcon.2015.09.009