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ADDRESSING WASTE DURING THE DESIGN PHASE: A MATRIX MODEL FOR THE INTERACTIONS BETWEEN ROBOTIC SYSTEMS AND LEAN PRINCIPLES

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ABSTRACT

This paper aims to provide a visual model with design parameters that are specific to manufacturing to reduce waste in the design stage of a construction project. More construction companies are interested in reducing waste and increasing efficiency. However, one of the main barriers that prevent the construction industry from adopting more technological solutions for its projects is not being clear about the direct benefits that would be obtained. This paper proposes using design parameters applied in a user-friendly visual model to choose the benefit to obtain for designing a construction project. These benefits are displayed as key performance indicator (KPI) options for the construction project. An analysis was carried out in a matrix to obtain the most relevant design parameters for a robotic cell in offsite construction from a manufacturing (not architectural or visual/aesthetic) point of view. Additionally, the visual model is designed using a data visualization structure. The limit of the investigation involves not having the visual tool validated in a case of a real construction company. Additionally, the visual tool is only a guide that is not quantified.

KEYWORDS

Key Performance Indicator, Design parameters, Construction industry, Lean, Industry 4.0.

INTRODUCTION

Errors and inconsistencies in the design are the most frequent factors contributing to the generation of waste in construction projects (Bajjou & Chafi, 2021). The efficient use of project resources depends mainly on the decisions made at the design stage (Sfakianaki, 2015). In an industry as competitive as construction, to survive, it is recommended to use

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new design technologies to consider environmental issues (e.g., environmental deterioration) at the design stage (Bajjou & Chafi, 2021).

Being an industry that involves projects of such great magnitude, such as buildings or hospitals, among others, that require so much labor that the traditional way of carrying out construction is no longer enough to meet the delivery of quality projects on time (Huang et al., 2021). Causing late delivery of projects that end up exceeding both budget and waste levels (Ofori-Kuragu & Osei-Kyei, 2021). The construction industry is being pushed to modernize and become more efficient (Bogue, 2018).

A technological advance that benefits quality and, at the same time, increases efficiency and reduces waste involves both robots and the application of lean principles (Huang et al., 2021). This combination allows a paradigm shift in the construction sector by introducing technologies that work together to eliminate waste (Ramani & KSD, 2019).

Robots play a crucial role in overcoming the limitations of traditional construction. Its use has several benefits: (a) reducing waste, (b) speeding up processes, (c) reducing costs, and (d) reducing production dependence on human labor (Bogue, 2018). The use of robots in offsite or on-site construction production frees up workers' time to focus on more value-added activities for the process (Gusmao Brissi et al., 2021).

The application of lean principles in the construction industry encompasses the benefits of (a) minimizing construction waste, (b) increasing customer satisfaction, (c) higher productivity and reliability, and (d) more safety (Khaba & Bhar, 2017). This application includes a wide range of techniques such as just-in-time, six sigma, and pull planning that is related to (1) design and engineering, (2) planning and control, (3) construction and site management, and (4) health and safety management (Gusmao Brissi et al., 2021).

The main problems architects/managers face in the design stage are last-minute changes by the client, followed by design changes and detailing errors. Which ends up using more time to develop the project and a huge generation of waste (Olanrewaju & Ogunmakinde, 2020). It is important to note that making bad decisions at the design stage results in a significant increase in the amount of waste that will be generated throughout the project (Othman & Abdelrahim, 2019).

On the other hand, one of the main barriers to countering the problem of waste generation at the design stage is the lack of construction waste minimization training and waste accepted as inevitable. As a result, we will concentrate on the design stages of a construction project since it is one of the most challenging where it is required to have a good level of adaptability to adjust to the changes requested by the client without this representing an increase in the waste levels of the project (Olanrewaju & Ogunmakinde, 2020).

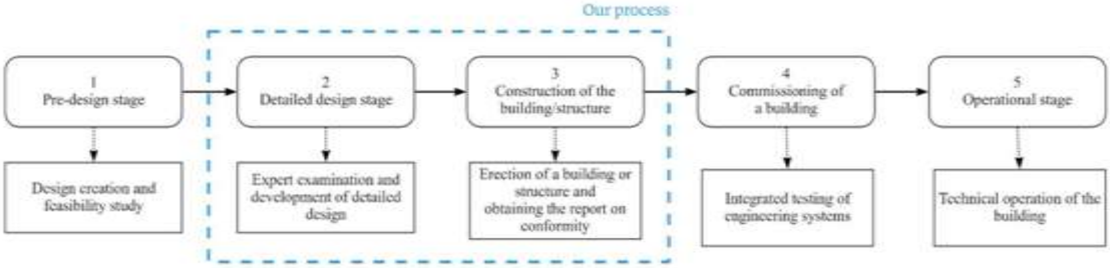

Figure 1: Sequence of construction phases, adapted from (Topchiy & Kochurina, 2018).

The relationship between waste and efficiency during the design stage of a construction project has not yet been clarified when linked to the outcomes that are expected from the building. Therefore it is not evident which path needs to be followed to meet the project's outcomes while facing the previously mentioned challenges regarding last-minute changes without causing errors and reducing important related factors such as waste in the construction operations during the design phase. As shown in Fig. 1, steps 2 and 3 are the focus of our process, these construction phases start as a linear sequence, but in the two previously mentioned steps it is where they go back and repeat themselves due to last-minute modifications, which are costly and wasteful. The objectives of this project are: (a) The definition of the relationships between design parameters of the robotic cell and processes derived from KPIs of manufacturing processes. (b) The outcome of a matrix model is linked to a system through a visual tool. This implementation aims to validate the presented approach and open the discussion of addressing construction waste during the design phase.

METHODOLOGY

The presented research study is based on the findings reported in (Gusmao Brissi et al., 2021) on the interactions between robotic systems and lean principles (Gusmao Brissi et al. 2021). The authors performed a systematic literature review to identify the journal papers that addressed the interactions between automation and lean, then focused on the under-researched topic of robotic systems. This allowed the categorization of construction automation and the presentation of the different interactions between lean and robotics in a matrix.

Table 1: Integration of the interactions of the lean and robotic system following the methodology adapted from (Gusmao Brissi et al., 2021).

Principal area	Approach
Eliminate waste	*Reduction of waste during the design phase* Reduction of construction waste through the application of the analysis result shown by the interactive visual tool in the construction project.
Flow process	*Increased flexibility* Increase of design adaptability in last-minute changes through the dynamics of the visual tool where the user can change a specific parameter and in real-time receive an update of what other parameters must be reduced or increased in order to continue meeting the selected KPI.
Value generation process	*Ensuring accurate design parameters capture* Use of established design parameters that cover the different data that are needed to be able to fulfill a KPI.
Problem-solving	*Evaluate parameters decision* Decision by consensus, consideration of all options (reduction and/or increase of a design parameter) in order to define what is the best decision for the development of the construction project.

It was argued that the interactions between lean principles and robotics were more noteworthy in the manufacturing stage and on-site construction phases; however, it should enhance construction operations from the design phase of the construction project. This study explores the methodology used by Gusmao Brissi et al., describing in more detail the interactions described between lean and robotic systems as a matrix (Gusmao Brissi et al., 2021). The developed approach is then implemented in a robotic cell in an offsite manufacturing environment for producing the required panels for a construction project during the design phase. Table 1 summarizes the presented approach from a lean perspective following the reported methods.

ROBOTIC SYSTEMS AND LEAN INTERACTIONS - MATRIX MODEL

As aforementioned, a matrix model is proposed to describe how the design parameters (DP) for a robotic cell in offsite construction interact with major lean wastes (LW) that are applied to the pre-defined key performance indicators (KPI). This project is not focused on the initial design of the product but on the part of the design for manufacturing of construction components. This matrix is an initial proposal covering a series of parameters related to robot selection criteria, cell requirements, and lean wastes; but does not try to be a comprehensive list of all the possible design parameters as that task could prove itself gargantuan.

Table 2: List of the design parameters and lean wastes used for the matrix model in this study.

Robot selection criteria	**Production requirements**	**Cell requirements**	**Lean wastes**
D1 – Robot payload	D6 – Time in of the input material	D15 – Area of the robotic cell	L1 – Inventory wait time
D2 – Robot accuracy and reach	D7 – Cycle time for each process in a station	D16 – Total number of robots in the cell	L2 – Transport time
D3 – Robot speed	D8 – Changeover time	D17 – Number of tools used by a specific robot	L3 – Non-value-added motions
D4 – Number of axes of the robot	D9 – Idle time	D18 – Tool accuracy	L4 – Robot(s) idle time
D5 – Robot linear motion speed	D10 – Stock size of the product	D19 – Total number of tools used to produce one unit	L5 – Defective parts - rework
	D11 – Size of the product	D20 – Distance between the stations	L6 – Defective parts moved to scrap
	D12 – Scheduled maintenance time	D21 – Traveling speed of linear motion systems	L7 – Material waste produced
	D13 – Minimum number of cycles required per day	D22 – Total number of operations required to produce one unit	L8 – Over-processing
	D14 – Scrap removal time for one cycle	D23 – Total number of workstations	L9 – Underutilizing the robot capacity
		D24 – Path efficiency	L10 – Machine downtime
		D25 – Number of operations required for providing the input material	

The design parameters are classified into three categories: (a) robot selection criteria, (b) production requirements, and (c) cell requirements. The design parameters and lean wastes are identified through previous exhaustive literature reviews and observations of industrial robotic cells. One of them is later used as a case study. A list of the design parameters is provided in Table 2 alongside the major lean wastes targeted for this study.

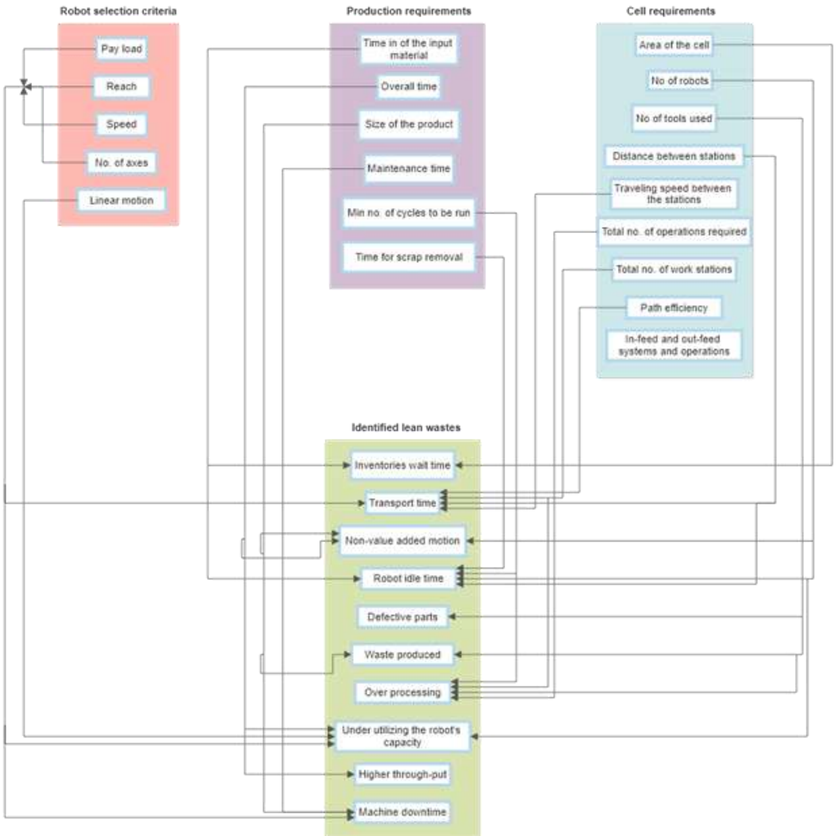

Figure 2: Various effects of design parameters on lean waste.

The matrix model then represents how the different parameters and lean wastes interact with each other on a one-on-one basis. Figure 2 shows the internally generated links between all the design parameters and the lean wastes. Figure 3 illustrates the model generated for the parameters in Table 2. This model determines how the different parameters influence others; the "+" symbol represents a positive interaction (e.g., proportional increments), whereas the "-" symbol represents an inverse interaction. A blank space represents that there is no known effect or correlation between parameters, and, in the case of a "±" symbol, it indicates that a known effect is known but is either not measurable or variable; therefore, it changes its interactions depending on the conditions of the other parameters.

Proportional effects	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
D1										+	+		+			−																			
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D7	−	−	−	−	−	+					+					−	±	−	±			±	±							+			+		
D8	−			−						+	+					−	+		+			±	±							+					
D9	−	−	−	−	−	+		+		+	±			+	+	+	−		−	+	−	±	±	−	±	+	+	+	+	+		+	+		+
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L1						+	+	+	+					+	+					+	−			−	±		+	+	+				+		+
L2										+					+					+	−		+	−											
L3		−	−	−				+		+	+					−				+	−		+	−			+								
L4	−	−	−	−	−	+	+	+	+	−	−		−	±	+	+	−			+	−	±		−	±	+	+	+		±	−	±	−	+	+
L5		−										−						−																	
L6		−										−						−																	
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L9	±	±	±	±	−	+	+	+	+				−	±	+	+	−			+				−		+	+	+	+						
L10	±	±	±	±						+	+	−	+									+								+	+		+	−	

Figure 3: Matrix model describing the interactions between the design parameters and lean wastes selected.

For example, looking at the first row of Figure 3, the representation indicates that when parameter D1 is considered, design parameters D10, D11, and D13 are conditioned to proportionally behave in the same sense, i.e., an increase in D1 means an increase in D10, D11, and D13, while the inverse relationship can be observed with parameter D16. Similarly, suppose an increment is chosen for the parameter D2. In that case, it is expected that D3, D4, D10, D11, and D18 will also increase, whereas D16 will decrease, and D1 will be surely affected, but it is not possible to determine in which way.

Note that for the parameters that do not contain any symbol on them on each row, it means that a change in that specific parameter does not have a meaningful impact on those parameters. In that sense, one can identify parameters that are more "risky" or "interesting" as some change has an impact on many other parameters while others may be easier to control as changes may impact one or two parameters. In that sense, this matrix model enables designers to understand the implications of design decisions regarding robotic systems and their impact on waste. Therefore, construction companies will benefit from having this information to make the best decisions for the development of their projects.

MODEL VISUALIZATION

In order to facilitate the use of the matrix model in a more interactive way for designers and practitioners, a dashboard is designed that integrates the model information and allows designers to include their end goals for redesign or specific target areas of improvement. The model is then linked with an interactive dashboard for a user-focused approach to robotic system redesigning. An interactive visual tool is developed through Dash Plotly, which is a structure for building data apps in Python (Plotly, 2022) to test parameters' dynamics based on user input.

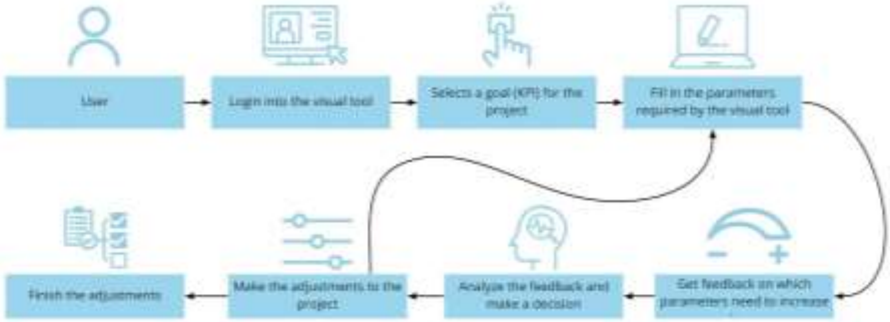

Figure 4: Steps to use the visual tool from the user perspective.

The interface is divided into two sections: the top side includes all the information related to user preferences and design goals. For example, a design analysis could be performed to target specific pre-defined objectives, such as: (1) minimize overall time, (2) maximize productivity, (3) minimize defects, (4) minimize the overall material waste produced, or (5) minimize overall waste, among other options.

Given a specific design goal, the user can choose which parameters are affected by the design changes, e.g., if the designer decides to pick a bigger size robot, then the design parameter D2 (related to the robot reach) can be assumed to increase. The design parameters previously listed in Table 2 are presented to the user to immediately have an answer to which parameters are directly affected by that change following the matrix model. Following that, the impact on the waste-related KPIs is presented, summarizing which wastes are being targeted by the redesign proposal and which areas can be further improved.

In summary, the dashboard allows the user entering the visual tool to choose the KPIs they want to focus on. Once the KPIs are selected, the design parameters that directly affect the selected KPIs are displayed for the user to enter the corresponding data. Once the data is received, the visual tool gives the user feedback on the design parameters that change following the matrix model and suggestions on further improvements to achieve redesign goals for the selected KPIs.

CASE STUDY

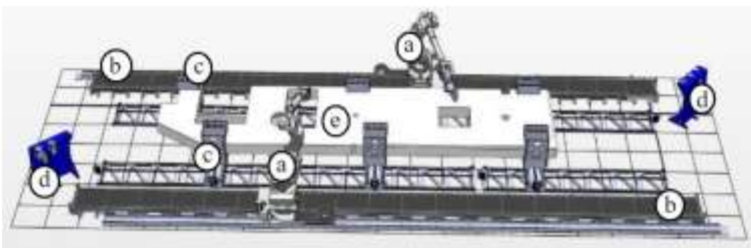

Figure 5: Automated robotic machining cell for cross-laminated timber panels. (a) Robot ABB® IRB 7600; (b) Track motion ABB® IRBT 7004; (c) Flexible clamping System; (d) Tool stand; (e) Minimum viable product (taken from Villanueva et al., 2021 with permission).

To validate the proposal, the redesign of an automated robotic machining cell for cross-laminated timber panels is used (Villanueva et al., 2021). This redesign aims to increase the robotic system's productivity, quality, and flexibility. Figure 5 shows the representation of the automated robotic cell, consisting of two robot arms that are positioned side by side on top of the track motion system allowing them to reach all areas of the workpiece. The design is simulated in @RobotStudio (design and simulation software), and the design parameters used for the design project are utilized as the input information to test the interactive dashboard.

Figure 6: Visual tool when selecting an objective.

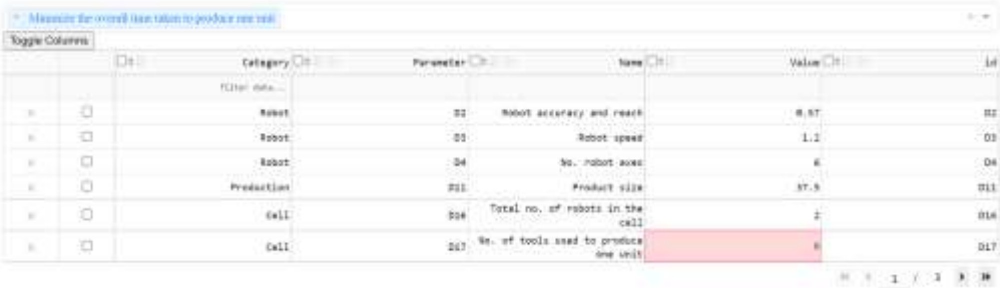

Figure 7: Visual tool with design parameters data table.

The first step was to select an objective to be addressed; in this case, KPI (1) related to minimizing overall time was selected, and subsequently, as shown in Fig.6. Subsequently, the dashboard displayed the design parameters that were conditioned to reach the chosen goal: D2, D3, D4, D6, D7, D8, D9, D10, D11, D14, D15, D16, D20, D21, D23, and D24, this can be found in Fig.2. Once these parameters were displayed, the design parameters that the project did have were filled in, where D1= 500kg (non conditioned parameter), D2 = 0.57mm, D3 = 1.2m/s, D4 = 6, D11 = 37.5m2, D16 = 2, D17 = 6, D23 =1. Once the data was provided, the feedback received specified that parameters D2, D3, D4, and D16 must decrease; indicating that the robot accuracy, reach, speed and the number of robots and robot axes considered for the design stage of the construction project should be reduced. Furthermore, it suggested that D11 must increase, stipulating that the construction panel/product should be expanded to achieve the KPI of Minimizing overall time for the project.

DISCUSSION

Using the proposed user-friendly visual tool for construction projects implies benefits where the user can directly understand the benefits that it can have for the project, and in the same way, he/she can decide what benefit he/she wants to obtain by selecting the KPI that most interests him/her for the project during the design stage that is manufactured in a robotic cell, and in this way evaluate the recommendations obtained. Additionally, the use of this interactive dashboard provides the characteristic of adaptability in the construction projects where it is used; if the project needs a change by the client, they only have to enter the new data in the dashboard to obtain what other parameters should be increased or decrease to continue meeting the objective selected for the project.

In this way, having to deal with last-minute changes by the client will no longer have such a significant impact on the project's development since immediate recommendations on how to act will be obtained. For example, if there was a last-minute change involving a different dimension from the panel for the construction project and the selected objective is "Minimize the overall time taken to produce one unit", the user only has to access the visual tool, update that parameter (D11: Product size) and the visual tool will automatically give feedback on which parameters need to be increased or reduced to continue meeting the initially selected objective. This means that the response time to know how to restructure the project properly will be fast and precise, avoiding, for example, the time and material waste involved in carrying it out.

The limitations of this application involve that the correlations used individually do not lead to waste reduction at any time because it is a decision/support that is based on something that is not quantified because the proposal is only a guide. This matrix needs to be used in simulation models to validate quantifications and decision-making. Additionally, other limitations involve not having a validation directly with real construction projects. In the same way, it is necessary to provide a specific range or percentage of how much it is necessary to reduce or increase each parameter recommendation feedback. Moreover, it is also needed to provide the user with a percentage of how close they were to the KPI selected by following the visual tool's recommendations.

CONCLUSION

The construction industry is undergoing a slow transformation but with an interest that has been growing over the last decade related to technology adoption (Ofori-Kuragu & Osei-Kyei, 2021). The industry has an important challenge where one of the barriers that prevent it from adopting new technologies is not being clear about the benefits that they will obtain by doing so, which is why when proposing the visual tool, it is expected that have a clear, direct benefit that the construction project will obtain, will encourage the construction industry to start to migrate to this type of digital solutions to increase efficiency and reduce waste in their projects. The proposed interactive dashboard is a highly visual solution that works as a guide to easily evaluate or re-evaluate the construction project design.

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