sustainability

MDPI

Article

Improving Construction Productivity by Integrating the Lean Concept and the Clancey Heuristic Model

Svetlana Besklubova * and Xueqing Zhang

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

* Correspondence: sbesklubova@connect.ust.hk

Received: 29 June 2019; Accepted: 16 August 2019; Published: 21 August 2019

Abstract: The profitability of most construction projects critically depends on construction productivity, which can lead to project cost overruns and schedule delays if not fully addressed. Although a literature review provides numerous worldwide examples of construction productivity improvement by mitigating and eliminating influencing disruptions through lean tool implementation, those studies considered a limited number of productivity disruptions in which the choice of lean tools was not clearly justified. This gap has significantly hampered the required improvements in construction productivity due to the limitations in selecting optimal solutions to fully overcome relevant disruptions and prevent their consequences. Hence, as a response to the aforementioned shortcomings, the present study develops the lean-Clancy-based decision-making matrix (LCDMM) that combines two different methods—the "Clancey heuristic model" and "lean construction"—with the goal of determining optimal and beneficial solutions to eliminate disruptions. The main thrust towards the adaptation of the matrix is based on its potential to link disruptions with solutions based on lean tools. In order to assess the practicality of LCDMM, the proposed solutions for two disruptions, as examples, are compared to existing practical solutions. Ultimately, it is clear that LCDMM, as a reusable tool, can assist scholars and practitioners in assembling the analysis of disruption waste and in selecting solutions for productivity improvement.

Keywords: Clancey heuristic model; lean construction; construction productivity; disruption

1. Introduction

Labour represents the most dynamic cost element in the construction industry [1] and can comprise as much as fifty percent of a project's total cost [2]; thus, maintaining a high level of construction productivity is one of the main goals of project managers [3]. Various reasons can initiate a construction productivity reduction; thus, enhancements in productivity would not be possible without identifying an area for improvement [4]. Many studies have attempted different methods to improve construction productivity, for instance studying the issues affecting construction productivity [5–8], modelling construction productivity [9,10], measuring and evaluating productivity [11–14], and comparing productivity based on economic considerations or costs [15].

Many identified productivity issues are unpredictable in the conventional management framework. The inflexibility of a conventional system does not permit a timely reaction to the variable conditions of the construction process. "Koskela has identified the inadequate conceptual foundations of traditional practices in terms of both management and project, and the resulting calls for reform offer new hope for a stagnant discipline" [16]. Therefore, "lean construction", an alternative management system, can be beneficial in dealing with construction productivity issues as an integrated approach with well-defined tools. It also creates a culture where problems occur less often due to a wide range of benefits such as waste reduction, decreased inventory, higher quality, greater system flexibility, reduced variability, and increased problem visibility [17]. The literature review provided numerous worldwide examples of significant construction productivity improvement by mitigating and eliminating issues through lean tools implementation [18–21].

However, those studies considered a limited number of productivity issues and the methods of selecting the lean tools used to eliminate those issues are not clearly justified. Thus, it is difficult to confirm that the implemented lean techniques are the optimal ones for mitigation and elimination of a particular productivity problem. In addition, in practice, the selection of appropriate lean tools could be limited by a project manager's own limited knowledge and experience. There are currently no practical guidelines for choosing lean tools to overcome construction productivity problems and this gap has significantly hampered the required improvements in construction productivity. Therefore, this research aims to develop a decision-making tool that assists in the selection of optimal lean techniques that might be used to overcome a particular productivity problem. In addition, this tool will reduce redundant searching, analysing, and reviewing of literature relevant to "lean construction" adaptation by scholars and practitioners whenever the selecting of solutions for productivity improvement is required. As different areas of construction (e.g., infrastructure, industrial buildings, post-disaster reconstruction) exist, it would be challenging to account for all those areas specified to create a decision-making tool; thus, we decided to limit the scope of this study to site-based production of building construction projects and specific construction tasks (e.g., painting walls, installing fixtures) as the most prevalently used projects.

2. Construction Productivity Disruptions

Productivity is a very old but still-relevant concept that corresponds to the ability to improve value and quality of services or products [22]. In other words, productivity is measured as the relation between output and input, where "input" consists of resources used in the product creation process, such as materials, equipment, and labour, and "output" inheres in a given product or service [23]. The term productivity can be applicable in measuring total labour productivity, crew productivity, project productivity, or even the productivity of particular resources, e.g., cash or construction equipment [23]. This general definition also aligns with Bröchner and Olofsson [24], Hanna et al. [2], and Page [25]. Figure 1 represents key features embodied in this productivity definition.

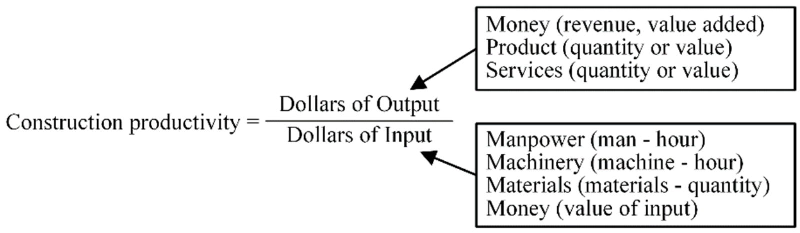

Figure 1. Equation of a general productivity definition (adapted from Durdyev [26]).

Construction projects can suffer due to a loss of productivity for a variety of reasons. Loss of construction productivity refers to a deviation in the productivity actually observed on a construction site from the productivity that might reasonably be expected [10]. A reduction in construction productivity can be caused by various disruptions [10], where "disruptions" generally refer to any event occurring on-site that unfavourably affects construction productivity [27] by converting a higher percentage of "input" into waste and not into finished products. Koskela defines waste as "any inefficiency that results in the use of equipment, materials, labour or capital in larger quantities than those considered as necessary in the production of a building" [28].

Over the years, considerable research efforts have been devoted to investigating the disruptions that decrease productivity by turning a higher percentage of used resources into waste [29–33]. Most of those studies obtained country-specific critical productivity factors, the differences of which were driven by the social, political, and economic environment of the considered territory [32]. A summary of those research findings drew a general picture of the current state of the art. Scholars have identified various productivity constraints and research approaches, namely the influence of change orders, the duration of overtime, and the length of shift work on labour productivity [2,12,34–36]; weather conditions [37,38]; dynamic modelling of labour productivity in construction projects [39]; action-response models on the loss of labour productivity [10]; and factors affecting specific construction task productivity [27].

Dai et al. [40] studied the factors that affected labour productivity from the craftworkers' point of view, where 1996 responses across 28 industry projects throughout the US were collected and analysed. Three areas with the greatest potential for project productivity improvement were indicated, as follows: Construction equipment, project management, and craft worker qualification. Rivas et al. [30] further extended this study by utilising a craftworker questionnaire to determine the influence of significant factors on labour productivity in a mining project in Chile. The results indicated that the major productivity factors are materials, tools, equipment, trucks, and rework.

From the perspective of construction professionals, Liberda et al. [41] determined the most critical factors affecting construction productivity in the Alberta construction industry in terms of "human", "external" and "management" issues. "Management factors" showed the highest relative result and accounted for half of the most critical 15 factors. El-Gohary and Aziz [3] also examined factors within three similar categories and ended up with the same result, where the influence of management factors on labour productivity in Egypt exceeded the other two categories, human and industry. However, Durdyev et al. [42] determined the critical factors affecting labour productivity in Turkmenistan, where the obtained results revealed that the most significant factors affecting labour productivity were the lack of local experienced labour, schedule pressure caused by the government, overtime work, financial weakness of the contractor, rework, inadequate financial policies of the government, and working seven days per week without a holiday.

A comparison of perceptions among project managers and construction workers regarding factors affecting construction productivity was revealed by Chan and Kaka [43], who conducted a survey in the United Kingdom. Project managers determined that supervision, the simplicity of building design, the level of site experience, information flow, and communication with sub-contractors are the top five significant factors. However, construction workers considered quality requirements, health and safety management, communication within gangs, utilization of plant, health and safety, and construction design and management (CDM) factors as the most important.

The above literature review showed that much attention has been paid to identifying factors and measuring their relation to productivity. Project managers should find ways to eliminate significant factors by leaning on their subjective experience, knowledge, and resources. Thus, it is crucial to provide a decision-making tool that can assist in obtaining solutions for emerged disruptors accounting for a particular construction project specificity, which is the aim of this study.

3. Using Lean Philosophy to Improve Construction Productivity

Once an area is identified for construction productivity improvements, management should then work towards and maintain the improvements over time [4]. In this regard, "Lean construction", an alternative management system with well-defined tools, is introduced in the current study to assist in improving the construction process and increasing productivity [17]. One of the top priorities in lean construction theory is eliminating waste in a process [44–46], which is a consequence of disruptions that affect construction productivity. Furthermore, a wide range of lean theory benefits have been listed including the following: A reduction in waste, production cost, production cycle time, labour and inventory; an increase in quality, profit, and system flexibility; and an improvement in cash flow and the capacity of existing facilities [17].

Regarding the lean concept, Koskela [28], in his early work, introduced the construction process as a flow of processes called "workflow", which includes the movement of resources and information through a system. There are four important components (flows) of the workflow, as follows: Manpower, material, equipment, and information [47]. "Manpower flow" is the tracking and allocation of the labour resource to various construction tasks and the interaction of the crew with other crews and other work [47]. "Material flow" involves the tracking of raw materials, pre-fabricates, parts, components, integrated objects, and, finally, products from suppliers and fabricators to the construction site, as well as their allocation for executing various work assignments. "Equipment and tools flow" involves the tracking and allocation of the tools and equipment for executing various work assignments. "Information flow" is the movement of information among various construction project parties. Later, Koskela further developed this idea and formulated the Transformation–Flow–Value (TFV) theory that is commonly seen as the main theoretical foundation of lean construction [48]. The production "transformation" (T) refers to the transformation of raw materials and parts into products through the use of machinery, energy, and labour. The "flow" (F) is related to flow in time and space. The "value" (V) perspective focuses on the external output of the process (Koskela, 2000) [49].

Disrupted flow turns resources into waste. One of the pioneers of lean thinking, Shingo [50], proposed seven types of waste, as follows: Overproduction, waiting, transporting, over processing (too much machining), inventories, moving, making defective parts and products. In addition, Koskela [28], in his early work, recognised waste in construction processes as a number of defects, design errors and omissions, rework, the number of change orders, and excess consumption of materials. The invented TFV theory generates three main categories of waste, as follows: Material waste (non-optimal use of material, non-optimal use of machinery, energy, or labour); time loss (unnecessary movement, unnecessary work, inefficient work, waiting), and value loss (lack of quality or defective products, lack of intended use, harmful emissions, and injuries and work-related sickness) [48]. Koskela [51] also proposed an additional category of waste named "making do", which refers to a situation where a task is started without all its standard inputs or continued although the availability of at least one standard input (e.g., materials, tools, equipment, manpower, information) has ceased [51]. Koskela's waste types are significantly different from Shingo's classical list of waste types, which focused on flow and not on the transformation perspective [48]. Serpell et al. [52] further identified that productive time is wasted by work inactivity and ineffective work. Many other researchers, such as Barbosa et al., Hosseini et al., Sacks and Goldin, Sullivan et al., and Womack and Jones [19,53–56] provided waste classifications that have similarities with each other. In addition, Sarhan el al. [57] established the novel concept of "institutional waste within construction" that explains how the systems, structural arrangements, and cognitive undergirding assumptions support and encourage wasteful activities in construction. More specifically, institutional waste is defined as "the regulative, normative, and cognitive culture institutional processes which support and/or encourage wasteful activities, that the construction industry (organisation field) accedes to in the form of habitual, imitation or compliance; in order to achieve legitimacy, security and survival at the price of production efficiency and effectiveness" [57,58]. All types of waste should be considered for elimination by lean tools.

Lean philosophy is based on a number of principles, the foundations for a field of knowledge, which consist of fundamental truths, rules, laws, doctrines, or motivating forces on which other more specific operating principles can be based [59]. Both Womack et al. [60] and Koskela [28] utilised the term "lean principle"; however, authors provided a varying classification of principles. Womack and Jones [56] presented value specification, value stream (waste elimination), flow, pull, and continuous pursuit of perfection as lean principles. Koskela [28] examined the eleven important principles in a context of construction production that arise from the "Just-in-time" (JIT) and "Total Quality Control" (TQC) concepts for flow process design and improvement, as follows: (1) Reducing the share of non-value-adding activities; (2) increasing output value through systematic consideration of customer requirements; (3) reducing variability; (4) reducing the cycle time; (5) simplifying by minimising the number of steps, parts and linkages; (6) increasing output flexibility; (7) increasing process transparency; (8) focusing control on the complete process (appointing a controlling authority such as a stakeholder responsible for the efficiency and effectiveness of cross-functional processes in hierarchical organizations; self-directed teams that are allowed to control their processes; long term co-operation with suppliers and team-building for inter-organizational flow control); (9) building continuous improvement into the process; (10) balancing flow improvement with conversion improvement; and (11) performance measurement [28]. Koskela's principles do not contradict Womack et al., but rather includes them in his theory, such as the idea that JIT includes pull, flow, and the continuous pursuit of perfection. Thus, the principles of Womack et al. [60] can be described as the general characteristics of lean philosophy aimed at the reduction of production process waste [61]. However, Koskela's principles can serve as an implementation guideline [28]. Each lean principle is implemented through various lean techniques that are defined as the specific instructions of lean principle implementation on a construction site. A technique can be considered as lean if it allows the elimination of construction activity waste [62,63].

Lean philosophy has been applied in such construction-related areas as infrastructure projects [64,65] and post-disaster reconstruction [66], with an evaluation of stakeholder attribute influences on the performance of disaster recovery [67]; however, the focus of this paper is on site-based production of building construction projects, as was previously mentioned. Ala-Risku and Kärkkäinen [20] proposed a potential solution for managing construction project material logistics, the poor organization of which is one example of productivity disruption. A shipment tracking-based software system was proposed, based on the Last Planner technique, in order to provide inventory transparency and short response times in the supply chain. Grau et al. [68] further extended this study by quantifying that material tracking technologies can significantly improve craft labour productivity.

The aforementioned Last Planner has been utilised in the research of AlSehaimi et al. [18] to evaluate this lean technique's effectiveness in improving construction planning and site management practice in the Saudi construction industry. However, Shehata and El-Gohary [69] proposed the implementation of two lean construction techniques, namely "benchmarking" and "reducing variability", to improve construction labour productivity in Egypt. The results showed that benchmarking measurements are able to distinguish the best- and worst-performing projects and variability in the daily productivity data acts as an important delineator between well and poorly performing projects.

Salem et al. [61] studied the application of six lean tools in a construction project, as follows: Last Planner, increased visualization, huddle meetings, first-run studies, 5S (sort, set in order, shine, standardise, and sustain), and fail-safe for quality. The implementation of these lean tools helped in improving the relationship between subcontractors and general contractors, completing the project under budget within the set schedule, and reducing the incident rate.

Nerwal and Abdelhamid [70] estimated the sizes and schedules of crews working on the early stages of a construction project by implementing the "batch size" technique, which implied the determination of a reasonable number and composition of crews for effective task performance, with a significant reduction in idle time and zero work in progress. However, Ikuma et al. [21] implemented the Kaizen tool to improve framing crew work overall output by 55% in modular housing manufacturing.

A review of the literature shows that various lean tools have been implemented to mitigate and eliminate construction productivity disruptions. However, the list of considered disruptions is limited in each study and the methods of selecting lean tools to overcome them are not clearly explained. Instead, authors focused their attention on lean tool implementation details. Thus, it is difficult to conclude that the lean techniques employed are the optimal ones for a particular productivity disruption mitigation or elimination. The selection of appropriate lean techniques should not be limited by a project manager's knowledge and practical experience. Therefore, the need for a decision-making tool that assists in the selection of optimal lean techniques to overcome a particular productivity disruption is essential.

4. Clancey Heuristic Model

Although lean construction consists of various methods, it does not provide a framework that assists managers in choosing optimal lean tools to overcome productivity disruptions. A literature review extended to various scientific fields revealed the "Clancey heuristic model", which is aimed at classifying and determining a satisfactory solution by employing a structured framework [71].

Even though the heuristic model is a "fast thinking" method that, as argued, has limitations in accounting for only visible evidence as a source of knowledge [72], Clancey utilised this method in his study to develop a characteristic inference structure that systematically relates data (e.g., observations, unknown objects, or phenomena) to a pre-enumerated set of solutions, objects, events, or processes [71]. The "fast thinking" method is the process of learning from experience [72], which is well aligned with the current study that aims to aggregate the worldwide experience of construction management and lean implementation. The Clancey methodology for analysing problems is preparatory to building knowledge-based systems, examples of which are provided below [71].

The Clancey method is the process that consists of sequential parts—"data abstraction", "heuristic match", and "refinement"—which are depicted in Figure 2 [71]. "Data abstraction" is the process of hiding data details while maintaining the essential features of the data [73]. A "heuristic match" refers to the process of finding an appropriate general solution. "Refinement", which is the inverse process of "abstraction", consists of using a general solution such as input to generate more specialised ones; in other words, to go from abstract solutions to more concrete ones, the process of which applies domain knowledge on the solution [74].

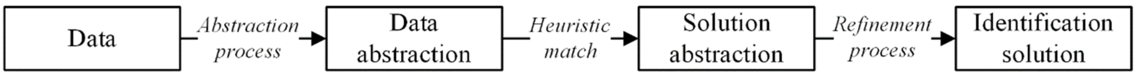

Figure 2. Clancey's heuristic model.

Motta and Lu [74] suggested using the following form of data abstraction $<f_i, v_i>$, where 'f_i' is a feature of the unknown object (or event, or phenomenon) and 'v_i' is its value. The following example represents the abstraction mechanism defined for the apple classification model that was developed by the University of Amsterdam [74], as follows: The quantitative reading of the sugar level in an apple to a qualitative feature, sweetness, the value of which can be "high", "medium", or "low". There were other types of features, such as colour, pattern, size, and taste, that were applied for the apple classification as well.

Previously, the Clancey method was used for well-structured problems in medicine, biology, psychology, software engineering, etc. [71]. One of the existing applications of the Clancey heuristic model is the MYCIN program, which was developed to advise physicians in the diagnosis and treatment of infectious diseases. Basic observations about the patient are abstracted into patient categories, which in turn are linked to disease categories and particular diseases [75]. Another application of the Clancey model is GRUNDY, a library system that builds models based on user stereotypes and then exploits those models to suggest novels that people may find interesting. GRUNDY classifies a reader's personality, which is linked to relevant book classes, and then selects particular books appropriate for this kind of person [76]. There is also SACON (Structural Analysis Consultant), an "automated consultant", which advises non-expert engineers in the use of a general-purpose structural analysis program. SACON at first simulates the behaviour of a physical structure and then uses classification to select a program [75,77]. In addition, SOPHIE classifies the components of faulty electronic circuitry. SOPHIE's set of pre-enumerated solutions represents a lattice of valid and faulty circuit behaviour [78].

Thus, the "Clancey heuristic model" can be transferred and adapted to solve the current research problem as its logical structure can assist the process of selecting optimal lean tools to reduce or eliminate disruption influences. All three introduced stages of "Clancey's heuristic model" ("abstraction", "matching", and "refinement") are involved and integrated with the aforementioned components such as "disruptions" and "lean techniques" to achieve the aim of this study. Preliminarily identified disruptions are used as input data that, through the "abstraction process", are represented as "disruption abstractions". The "heuristic match" is implemented by matching "disruption abstractions" with "solution abstractions" that are represented as "lean technique abstractions". Each "lean technique" in its turn is determined to be a "solution", the optimal and beneficial of which are identified for each disruption through the "refinement" process. In order to elaborate on each mentioned step of the "Clancey heuristic model" and lean construction integration, the methodological approach was developed and is discussed in the section below.

5. Methodological Approach

To apply the "Clancey heuristic model" for the purpose of selecting optimal lean techniques to eliminate disruptions, the processes of "abstractions", "matching", and "refinement" were elaborated by using a combination of research methodologies as follows. The list of disruptions, lean tools, and waste types for the abstraction process (disruptions and lean technique abstractions) have been identified through the structured review approach. A disruption abstraction process was held by conducting focus group interviews with industry experts. As a result, the lean-Clancy-based decision-making matrix (LCDMM) was developed to address the matching process for use by construction parties. The overall methodologic approach is depicted in Figure 3 and is discussed below.

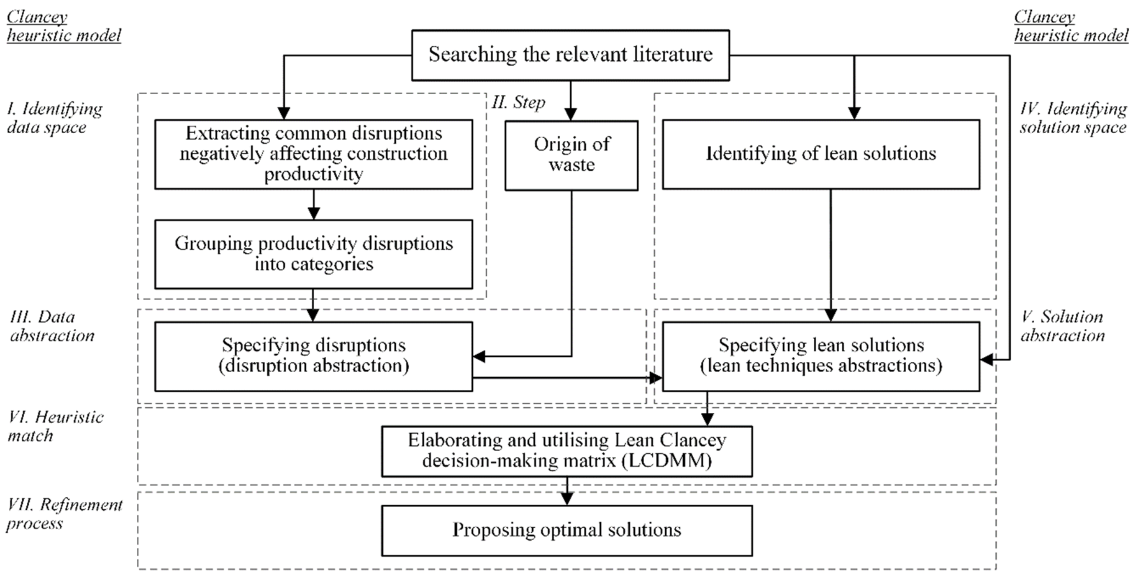

Figure 3. Methodological approach.

5.1. Extracting Common Disruptions Negatively Affecting Construction Productivity

Previous research provides a basis for identifying productivity disruptions. To identify relevant scholarly articles for further analysis, the current study adapts the systematic method introduced by van de Vijver, which includes three main steps [79]. The main reasons for exploiting van de Vijver's structured review approach are threefold, as follows: Firstly, the concept of originality was followed (specific timeframe, English language use, and engineering-related area were set for the screening). Secondly, the concept of domain-specific works was taken into consideration (works discussing construction productivity disruptions were extracted during the screening). Finally, the concept of most contributed works was considered (the citations assigned to each paper were very carefully taken into account for the screening). The above mentioned three steps involved in van de Vijver's structured review approach are as follows.

The first step, a comprehensive keyword search for "construction productivity" and "labour productivity" in diverse scholarly studies published in the Scopus databases was conducted [79,80]. Logical reasons to adopt Scopus as the search engine were clearly explained by Yi and Wang [81]. A broad perspective in selecting articles on construction labour productivity was used, including those dealing with significant factors that identified survey-based studies, case studies, conceptual papers, modelling approaches, and productivity problem mitigation. Such a broad definition was warranted given that this first selection was made based on the article title, abstract, and keywords. For example, an author might have chosen to use "construction productivity" in titling an article focusing on key influential factors. The same line of reasoning holds for other types of productivity research. Due to the extent of the study domain, a set of filters was implemented to limit the number of articles that were not specifically relevant to the scope of the study [80]. The first filter was set out to include past research published in accredited sources from 1989 to 2019. Exclusion of languages other than English was carried out through the implementation of the second filter. A third filter was set to exclude subject areas that did not relate to engineering. In the second step, the content of each article was analysed by examining the abstract, research method, conclusions, and discussion sections [79,82]. This step helps to assess the suitability of selected domain-specific works for the purposes of the current study. In the third step, the citations were used to define a measure of scientific significance [83]. To select the most relevant articles, the list of studies was organised from the most to the least cited, then the papers that corresponded to 80% of the citations (considering the cumulative sum) were selected. Recent articles, published less than four years before this analysis, did not have enough time to be widely cited and were brought back to the portfolio [83]. Details of the search, including the number of papers that appeared in the Scopus search engine using inclusion and exclusion criteria are specified in Appendix A, Table A1.

The number of disruptions related to financial issues was limited in the disclosed scientific articles; thus, additional searching was conducted to delve into this topic and obtain various financial disruptions. Van de Vijver's same three steps (keyword search, paper content analysis, and papers' scientific significance assessment) [79] were repeated to disclose scientific papers tagged with "cash flow" combined with "construction".

A finalised list of disruptions was obtained by eliminating any redundancy that various publications used for disruptions having the same functionality. In addition, rarely encountered factors specific to a particular territory/country were excluded from further analysis.

5.2. Grouping of Productivity Disruptions into Categories (Identifying Data Space)

Disruption classification is used to manage determined disruptions by dividing them into categories. The various construction productivity disruptions can generally be categorised into five groups, called the 5Ms, which are management (method and control), money, manpower, materials, and machinery. The "machinery" category is renamed "equipment and tools" in order to make this category more comprehensive, where "equipment" includes machinery. According to Halligan et al. [10], the basic causes of productivity loss also include external conditions, which are determined as events, situations, and decisions beyond the control of contractors or crews. Furthermore, the names of disruption categories coincide with the names of flows, the exception being "management (method and control)" disruptions that destabilise the information flow or whole workflow. Thus, such disruption categorisation makes it clear which flow a particular disruption affects.

As lean philosophy is an alternative managerial approach, correspondently, all considered disruptions have to be under the control of construction project managers who deal with them by means of integrating this philosophy. Thus, disruptions and their categories are reassessed to meet this condition.

5.3. Origin of Waste

Disruptions decrease productivity by turning a higher percentage of used resources into waste [29–33], the types of which should be recognised in order to relate them to specific disruptions. Types of waste as the basis of lean concepts [84] were searched in the aforementioned search engine (Scopus). The terms used in the database search were "lean" and "lean philosophy" combined with "construction". English peer-reviewed journals up to 2019 came to light, the following examination of which, according to the van de Vijver methodology discussed above (keyword search, paper content analysis, and papers' scientific significance assessment) [79], disclosed the scientific papers using process waste classification. Details of the search with the number of papers that appeared in the Scopus search engine using inclusion and exclusion criteria are specified in Appendix A, Table A2.

A pivot table was created, which assists in creating a comprehensive list of process waste types by comparing the lists of waste from the selected studies.

The current study examines each type of waste in order to ensure that it can be a consequence of identified disruptions. For this purpose, a focus group interview was conducted, which is controlled group discussion intended to obtain participant perceptions regarding specific topics in a defined environment [85]. Expert panel members were selected based on an experienced-based selection method; thus, they had to meet at least two of the following criteria: (1) Be employed in practice with at least 5 years of experience in the construction managerial process; (2) be employed as a faculty member at an institute of higher learning; (3) be involved as a primary or secondary author of at least three peer-reviewed journal articles; (4) be invited to present a paper at a conference; (5) be a member or chair of a nationally recognized committee; (6) have an advanced degree in the field of civil engineering, CEM, or other related fields (minimum of a BS); and (7) have a professional registration such as Professional Engineer, Licensed Architect, Certified Safety Professional, or Associated Risk Manager [86]. An optimal size for focus group studies is 6–12 participants [85]. In the current study, eight experts from Chinese, Iranian, Indian, and Pakistani construction industries participated.

Prior to the focus group interview, participants were asked to complete a form that confirmed whether the proposed waste obtained, based on the literature review and the authors' experience, was the consequence of each disruption by marking "yes" or "no", or adding where a disruption required some type of waste from the proposed list. Panel members were also allowed to modify the name of the waste by adding some specificities or details, which provided a proper description of disruption.

Based on the results, another form for the discussion was prepared that contained expert disagreements and suggested additions of disruption waste. Thus, the focus group discussions were organised according to the same semi-structured framework to clarify those expert disagreements and to validate additions. During the discussion, a moderator showed on-screen disruption waste that needed to have consensus and allowed all participants to review ideas, provide feedback, and finally, produce a cumulative list. The important aspect was to encourage all participants to develop ideas collectively based on actual experiences related to the controlled discussion topics. This also helped to crosscheck the moderator's understanding, thereby minimizing the possibility of data misinterpretation. The focus group adjourned when there were no further comments.

5.4. Specifying Disruptions (Disruption Abstraction)

A "disruption" is used as input data that, through the "abstraction process", is represented as a "disruption abstraction". The "disruption abstraction" (DA) aims to express each disruption in a simple form, which helps with the "heuristic match" [74]. By adopting the idea of Motta and Lu [74], for the purposes of the current study, each disruption can be characterised by using two features, as follows: (1) "Flow type" by which disruption happens with four possible values (manpower, material, equipment and tools, or information) and "waste types", which are the consequences of disruption with values from the validated disruption waste. A short version of each disruption can be represented as a pair in the form DA $<f_i; w_i>$, where 'f_i' is a flow and 'w_i' is a type of waste. For example, the abstraction of the disruption "extensive multiple-handling of materials" can be represented as <material flow, unnecessary movement>. Some disruptions can have more than one "waste type" (w_i), so all of them should be listed.

5.5. Identification of Lean Solutions

A search for scientific papers in order to obtain the types of process waste was undertaken again to classify lean principles and techniques (see Appendix A, Table A2). Koskela's lean principle classification was used as a base for lean techniques obtained for the current study as it was recognised across a variety of studies, such as Abdel-Razek and Abdel-Hamid [87], Barbosa et al. [19], Sacks et al. [88–90], and Salem et al. [61]. Before involving lean philosophy in a decision-making matrix its techniques should be systematised. Koskela [28] mentioned basic techniques for each principle; however, since that time some new applications have been proposed and implemented in practice. Thus, those applications should also take a place in Koskela's lean technique classification. Therefore, a comprehensive list of lean techniques, which has so far been lacking in previous scholarly work is here presented with a strong literature backing.

5.6. Specifying Lean Solutions (Lean Techniques Abstractions)

"Lean techniques" are used as input data to represent "solution abstractions", here named "lean technique abstractions". The same Motta and Lu's [74] method of simple expression is also applied to formulate a "lean technique abstraction" (LTA), the match of which with a "disruption abstraction" would be clear. "Lean technique abstractions" can be represented as the form LTA $<f_i; w_i>$, where 'f_i' is a "flow" with which disruptions occur (manpower, material, equipment, and tools or information), and 'w_i' is a type of waste that can be reduced by lean techniques, where 'w_i' can take multiple values. A validated list of waste types (according to Section 5.3) as disruption causes is used for "lean technique abstraction", as all those wastes should be eliminated by different lean implementation techniques. Thus, the literature of lean concept implementation is revised again to confirm a specific type of waste in relation to flows that can be overcome by each lean technique.

5.7. Elaborating and Utilising LCDMM (Heuristic Match)

Types of waste and flow assigned to each lean technique as its abstracted form, based on the literature review, are represented in the long list of a dataset that is difficult to manage and work with in order to obtain a solution for a disruption. Thus, it was decided to represent this dataset as a matrix—the lean-Clancy-based decision-making matrix (LCDMM)—for the convenience of obtaining disruption solutions ("heuristic match") by project managers. The matrix includes types of waste in the first column and lean techniques in the first row. The matrix intersections display the flow types to which corresponding waste and lean techniques are applicable. For the "heuristic match" process execution, responsible construction parties should compare "disruption abstractions"—DA $<f_i, w_i>$—with the decision-making matrix that represents "lean principle abstractions"—LTA $<f_i, w_i>$: DA $<f_i, w_i>$ = LTA $<f_i, w_i>$.

5.8. Proposing Optimal Solutions (Refinement Process)

Once suitable lean techniques are identified through the "heuristic match", the process can move to the follow-up stage through the "refinement process" to find optimal and beneficial lean techniques, which should be chosen from the proposed lean technique options. Here, a close look at the lean techniques can assess which ones can be applied to account for disruption specificities, site conditions, and available resources for lean technique implementation.

6. Results

6.1. Extracting Common Disruptions Negatively Affecting Construction Productivity

After applying the filters that limit the scope of the papers, visual examination followed by citation investigation resulted in the selection of 78 target articles relevant to the study, which provide a basis for identifying labour productivity disruptions. In an example of disruption redundancy, Lim and Alum [91] used the term "inclement weather" and Rojas and Aramvareekul [92] used the term "adverse weather conditions". The current study dispenses with this redundancy ("inclement weather" and "adverse weather conditions") by using the term "adverse weather", defined as unfavourable weather conditions such as high/low temperature or humidity, strong wind, snow, heavy rain, etc. The finalised list is comprised of 41 disruptions that are identified by previous scholarly works and represented in Table 1.

6.2. Grouping of Productivity Disruptions into Categories (Identifying Data Space)

During disruption categorization, it was observed that some of the categories required special attention due to their ability to be mitigated by lean tool application. Such categories as "external disruptions" were re-examined as they cannot be controlled by the contractor, who is a responsible party, and can take managerial decisions only in term of disruption consequences, but not root causes [10]. For example, a workday was disrupted by weather (external disruption) because measurable time was spent clearing snow from the construction site; in turn, this initiated schedule changes and acceleration [37], which contractors needed to deal with. Other examples of external disruptions are an unfavourable economic and financial environment, unfavourable political environment, social injustice and cultural, issues and the slow government approval process [3,30,31,41,91,93–95]. Accordingly, external disruptions are not elaborated in the current study, but they are considered as consequences, such as the aforementioned "schedule changes and acceleration" under the "management and control" category.

Special attention has also been paid to the category "money". Disruptions related to this category appear on a construction site due to external factors (e.g., market instability) and poor cash flow management [96,97]. Disruptions that are initiated by external entities are beyond the control of both the owner and the contractor [98], for instance, difficulties in getting loans from financial bodies, inflation (material prices, labour wages, transportation costs) foreign exchange rates (imported materials and plant), loan repayment interest rate increments, etc. [33,96,99]. Thus, those disruptions are excluded from the list for further consideration.

However, problems related to management actions or resource allocation are still considered in this study; for instance, examples include delay in payment resulting in slow progress on site or failure of material delivery to the site, as many sub-contractors and suppliers are subjected to financial difficulties [97]. Therefore, capital flow should be connected with resource utilization to reflect the actual expenditures and resource assignments for scheduled construction tasks [100]. Thus, changing the management approach from the conventional to the advanced lean system will have an influence on capital distribution; for example, resource management with small inventories and reliable flow, instead of large work-in-process inventories and inflexible operations, results in better capital distribution [53]. Correspondently, cash flow is inextricably linked to workflow or its particular components such as material flow (a lack of money involves material supply problems). The categorised list of disruptions is represented in Table 1.

Table 1. Disruption list.

Disruptions Category	Code	Disruptions	Relevant Literature
Management (method and control) disruptions (MG)	MG1	Poor qualification/experience of management at different levels	[29,32,41,95,101]
	MG2	Inadequacy of planning and risk management process	[33,102]
	MG3	Inappropriate construction method	[33,102]
	MG4	Schedule changes and acceleration	[33,93]
	MG5	Relationship management/degree of harmony, trust, and cooperation	[26]
	MG6	Slow management decision process	[32,103]
	MG7	Instruction time and supervision delay	[95]
	MG8	Inspection delays	[95]
	MG9	Poor supervision, performance monitoring, and control	[33,102]
	MG10	Improper crew size/composition	[29–31,41,101]
	MG11	Design changes, errors and omissions	[29,32,33,94]
Manpower disruptions (MP)	MP1	Improper coordination between different construction trades	[30–32,94,95,103,104]
	MP2	Low worker motivation	[31,41,94]
	MP3	Fatigue, mental and physical worker stress	[30,31,41]
	MP4	Physical worker limitations	[3,94]
	MP5	Worker absenteeism	[29,30,32,41,91,94,103,104]
	MP6	Worker turnover frequency	[29,32,91,95,104,105]
	MP7	Skilled/experienced worker shortage	[3,30,31,95,101]
	MP8	Indifference to worker opinion	[105]

Table 1. *Cont.*

Disruptions Category	Code	Disruptions	Relevant Literature
Equipment and tools disruptions (ET)	ET1	Tools and equipment unavailability	[29–31,94,95]
	ET2	Equipment breakdown	[106]
	ET3	Poor quality of power tools	[29,32,95,103,104]
	ET4	Improper tool/equipment allocation	[107,108]
	ET5	Unnecessary equipment movement	[107]
	ET6	Improper equipment capacity	[41,94]
	ET7	Transportation and/or equipment installation delay	[99]
Material disruptions (MT)	MT1	Extensive multiple-handling of materials	[30,31,94,109]
	MT2	Materials improperly sorted/marked	[109]
	MT3	Debris impeding material access/movement	[109]
	MT4	Late material delivery	[29,32,91]
	MT5	Material shortage at construction site	[30,41,93–95,103,104]
	MT6	Low fabrication shop production rates	[93]
	MT7	Poor material quality	[32,94]
	MT8	Delivery material out-of-specification	[99,110]
	MT9	Material damage from deficient stockpiling and handling	[99]
Money disruptions (MN)	MN1	Contractor's/subcontractor's unstable financial background/insolvency	[97,111]
	MN2	Contractor handles too many projects at the same time	[97]
	MN3	Completed work valuation inaccuracy	[96,97,111]
	MN4	Lack of regular cash flow forecasting	[33,97,99]
	MN5	Delay in payment to sub-contractors	[97]
	MN6	Delay in payment to suppliers	[97]

6.3. Origin of Waste

A search for relevant scholarly articles resulted in identifying 48 works applicable to this study, which therefore provides a basis for efforts to identify process waste for building construction projects site-based production. Different classifications of waste are synthesised in the current research. As waste classification is adopted from lean production, some waste types are removed from the construction process waste list. For example, "overproduction" (producing more than needed) [112] is removed, as construction is defined as production that produces a one-of-a-kind product that follows confirmed drawings and specifications [113]. Although, some of the authors defined "excessive transportation" as "excessive movement of people, information or goods, resulting in wasted time and cost" [53,55], which approximates to the definition of waste as "unnecessary movement or motion", the current study provides a difference between those two terms. "Excessive transportation" is related to insufficient equipment or material logistics from the factory to the construction site and the incorrect loading of resources in a truck (e.g., non-optimal loading composition), resulting in wasted time and cost [112]. However, the "unnecessary movement or motion" in its turn is interpreted as "poor workplace organization, resulting in poor ergonomics" [53]; in other words, double handling of material or unnecessary movement of the workforce, materials, and equipment on the construction site [54,112].

The waste "making do" is seen as a complex one that consolidates more than one waste type [57]. It can be considered as a variant of the "inefficient work" waste type, where the work is carried out in an inefficient way due to the lack of preconditions (e.g., resources, information) [57]. The waste type "waiting" of at least one standard task input (e.g., information, instruction, materials, tools, equipment, manpower) can be determined from the "making do" definition (provided in Section 3) [51,57]. The term "making do" is explained by Koskela in contrast to "buffering", which refers to resources that are waiting to be processed [51]. "Buffering" is a strategy where specific types of waste are used (e.g., material inventory) to establish a satisfactory level of flow and thereby reduce the total amount of waste in the system [48].

The focus group interview method helped to finalise waste types and designate them as consequences for each disruption. During the analysis of completed forms from experts, as a preparatory step for discussion, each example of disruption waste was deleted from the list if at least six experts out of eight voted to do so. Analogically, each example of disruption waste was confirmed. Other cases were considered as disagreements and were discussed during the focus group interview. All disagreements regarding disruption waste were resolved and some kinds of waste were specified by clarifying names to more accurately characterise disruption consequences. For example, the waste type "unnecessary inventories", which is the excessive storage and delay of information or products, resulting in excess inventory and costs leading to poor customer service [28,53–55,112], could be assigned to the disruptions "slow management decision process" (MG6) and "delivery material out-of-specification" (MT8). However, disruption MG6 relates to inventories such as delays in processing information and disruption MT8 relates to inventories such as materials and products; thus, it was decided to specify the type of waste as "unnecessary inventories" and to use two specific terms instead of the general one. The finalised cumulative list of waste and disruptions are correspondingly summarised in Table 2.

Table 2. Finalised list of waste types.

Code	Waste Types	Definition
W1	Improper sequencing of activities	This occurs when a crew task extends into an area or time covered by another crew [114].
W2	Waiting due to poor workflow planning	This arises due to long periods of inactivity due to inadequacy of planning/management decisions [19,53,112].
W3	Waiting for information (e.g., a decision, response, instruction) or resources	This arises due to long periods of inactivity as workers wait for information, equipment or materials (e.g., waiting for something to happen, waiting for others to finish) [19,53,112].
W4	Unnecessary movement	This refers to excessive movement of people, information, equipment or materials on the construction site, resulting in wasted time and cost [19,53,112].
W5	Defects	This relates to frequent errors in paperwork or material/product quality problems resulting in scrap and/or rework, as well as poor delivery performance [53].
W6	Ineffective work because of worker morale problems	This refers a slowdown in work processes due to worker morale problems.
W7	Ineffective work because of worker physical problems	This refers to a slowdown in work processes due to employing the workers with some restriction related to their physical disabilities [53].
W8	Ineffective work because of worker unavailability	This refers to a slowdown in work processes due to using the wrong worker crew composition [53].
W9	Ineffective work because of unqualified workers	This refers to a slowdown in work processes due to employing workers with low qualifications. [53].
W10	Ineffective work because of improper management decisions	This refers to a slowdown in work processes due to using the wrong procedures or systems [53].
W11	Ineffective work because of tool/equipment unsuitability	This refers to a slowdown in work processes due to using the wrong set of tools and equipment [53].
W12	Ineffective work because of poor maintenance	This refers to a slowdown in work processes due to the poor condition of tools and equipment.
W13	Number of setup or changeover times	This arises from frequently converting a piece of equipment from running one product to another or moving and installing equipment in another place [114].
W14	Unnecessary inventories such as delays in processing information	This relates to information delay resulting in excess inventory and costs, leading to poor customer service [53].
W15	Unnecessary inventories such as resources	This relates to excessive storage and delay of products, resulting in excess inventory and costs, leading to poor customer service [53].
W16	Excessive consumption of materials	This occurs when more materials are consumed than originally estimated.
W17	Not taking advantage of worker involvement in a process	This refers to a lack of teamwork that involves workers in improving the construction process [112].
W18	Not taking advantage of collaboration with supplier	This refers to a lack of teamwork involving the supplier in improving resource logistics to the construction site [112].
W19	Not taking advantage of collaboration among project parties	This refers to a lack of teamwork that involves various construction parties in improving and developing the different phases of the construction process [112].
W20	Improper choice of method	This arises from procedures or techniques that are unsuitable for complete task satisfaction and can depend on the capabilities of those who work on the project [115].
W21	Change orders	This occurs when the crew is forced to work in an illogical sequence that strays from the original [116].
W22	Design errors	This occurs when necessary components are erroneous or omitted, or when changes are made in a project design [117].
W23	Rework	This relates to unnecessary effort in redoing a process or activity that was incorrectly implemented the first time [117].
W24	Excessive transportation	This relates to insufficient equipment or material logistics from factory to construction site and incorrect loading of resources in a truck (e.g., non-optimal loading composition), resulting in wasted time and cost [112].

Table 2. *Cont.*

Code	Waste Types	Definition
W25	Unnecessary work	This relates to doing things that need not be done [48].
W26	Lack of intended use	This occurs when the purpose of the resources, products, processes or services are not fully explored and utilized [114].
W27	Undesired products	This occurs when a client is not satisfied with a completed construction product (e.g., apartments built to standard designs are less attractive to potential buyers) [54].
W28	Imperfect institutional processes	This relates to "the regulative, normative, and cognitive culture of institutional processes which support and/or encourage wasteful activities that the construction industry (organisation field) accedes to in the form of habit, imitation or compliance in order to achieve legitimacy, security and survival at the price of production efficiency and effectiveness" [57,58].
W29	Environmental uncertainty	This refers to the social-economical-political environment (e.g., fluctuations in the state of the economy comprised of factors such as inflation, changes to government macroeconomic policies and periods of instable of funding) [57].

6.4. Specifying Disruptions (Disruption Abstraction)

The focus group interview method helped to finalise waste types and designate them as consequences for each disruption; in other words, to formulate disruption abstractions. The finalised cumulative list of disruption abstractions is correspondingly summarised in Table 3.

Table 3. List of common disruptions abstractions.

Disruption Code	Flow	Caused Waste	Disruption Code	Flow	Caused Waste
MG1	Workflow	W10, W20, W25	ET1	Equipment and tools flow	W3, W24
MG2	Workflow	W2, W10, W25	ET2	Equipment and tools flow	W3, W5, W12
MG3	Workflow Material flow	W5, W20, W23 W16	ET3	Equipment and tools flow	W5, W12
MG4	Workflow	W21	ET4	Equipment and tools flow	W4, W13
MG5	Information flow	W18, W19, W28	ET5	Equipment and tools flow	W4, W13
MG6	Information flow	W14, W19, W28	ET6	Equipment and tools flow	W11
MG7	Information flow	W3	ET7	Equipment and tools flow	W3, W24
MG8	Workflow	W3, W21	MT1	Material flow	W4
MG9	Workflow	W5, W22, W23	MT2	Material flow	W4
MG10	Workflow	W10, W15	MT3	Material flow	W4
MG11	Workflow	W3, W22, W23	MT4	Material flow	W3, W18, W24
MP1	Manpower flow	W1, W2, W4	MT5	Material flow	W3, W18
MP2	Manpower flow	W6	MT6	Material flow	W3, W15, W18, W21
MP3	Manpower flow	W6, W7	MT7	Material flow	W5, W16
MP4	Manpower flow	W7	MT8	Material flow	W15, W18, W24
MP5	Manpower flow	W8	MT9	Material flow	W16
MP6	Manpower flow	W8	MN1	Workflow	W3, W10
MP7	Manpower flow	W5, W9, W23	MN2	Workflow Manpower flow	W3, W8
MP8	Manpower flow	W17, W26	MN3	Workflow	W3, W14
			MN4	Workflow	W3
			MN5	Workflow	W3

6.5. Identification of Lean Solutions

An examination of the lean techniques under each lean principle based on Koskela's [28] classification shows that some of the lean principles are reconsidered and merged with others as many principles are closely related and some are more fundamental while others are more application-oriented.

The principle "reducing the share of non-value-adding activities" dissolves in other Koskela [28] principles, as most of them address the suppression of non-value-adding activities. Another principle, "increasing output value through systematic consideration of customer requirements", contributes to other fundamental principles, especially "increasing process transparency" and "continuous improvement". The principle "increasing output flexibility" in its implementation techniques also coincides with other fundamental principles such as "reducing cycle time" and "increasing process transparency". In addition, the principle "balancing flow improvement with conversion improvement" implies financial investments in new conversion technology; however, the current study does not consider new technology involvement [28]. Thus, all the aforementioned lean principles are combined with other correspondingly mentioned Koskela principles and are not defined separately in the current study.

Therefore, the systematisation of lean techniques was conducted for the following fundamental principles: (1) Reducing variability; (2) reducing cycle time; (3) simplifying by minimising the number of steps, parts and linkages; (4) increasing process transparency; (5) focusing control on the complete process; (6) building continuous improvement into the process; and (7) performance measurement [28]. A finalised list of lean principles and techniques with their definitions is provided in Appendix B, Table A3 (see columns 1–3), with references to support the literature for lean technique classification.

6.6. Specifying Lean Solutions (Lean Techniques Abstractions)

For the purpose of the abstraction process, the previous research articles are revised to obtain a combination of waste types, which can be overcome by each lean technique and the corresponding flows. This process was realised by taking into account waste types that were obtained and justified during the disruption abstraction process (see in Table 3). The result is summarised in Appendix B, Table A3 (see columns 4–6), with references from the literature. It is noted that "performance measurement" is a leading lean principle dealing with disruptions by providing the information before the disruptions have had time to have any effect, which is crucial to support the implementation of lean construction [118,119]. Thus, implementing "performance measurement" as a leading technique to detect the possibility of problems is suggested.

6.7. Elaborating and Utilising Lean-Clancy-Based Decision-Making Matrix (Heuristic Match)

We represent the dataset from Appendix B, Table A3 as LCDMM (see Appendix B, Table A4) as a result of this research; thus, industry experts can utilize this matrix to obtain lean techniques for particular disruptions (heuristic match process). In a "heuristic match" the following cases can exist:

1. Finding "optimal solutions" where "disruption abstractions" fully match some of the "lean principle abstractions", e.g., DA $<f_1; w_1, w_2> =$ LTA $<f_1; w_1, w_2>$;
2. Finding "combined solutions", where "disruption abstractions" partially match some "lean principle abstractions" that can be combined to overcome all waste caused by the considered disruptions, e.g., DA $<f_1; w_1, w_2> = LTA_1 <f_1; w_1> + LTA_2 <f_1; w_2>$.

6.8. Proposing Optimal Solutions (Refinement Process)

A number of lean techniques can be identified through the LCDMM to overcome a disruption. Thus, the right to select only one lean technique as an "optimal solution" or a lean technique combination, such as a "combined solution", is left to project managers as they understand the environment and specificity of a particular construction project and the available resources for lean technique integration. In addition, in case any disruptions cannot be accurately formulated, all possible waste that they cause should be mentioned; the work then continues with all those wastes in order to obtain solutions.

Commonly, various combinations of simultaneous disruptions can be observed during a construction task execution; thus, the "abstraction" and "matching" processes are executed separately for each disruption. However, the "refinement process" accounts for the aggregation of all disruption waste.

6.9. LCDMM Validation

The most common framework for validation, which is widely accepted, can be attributed to Sargent's work [120]. According to this framework, validation of the proposed LCDMM to confirm its accuracy within the range of application is undertaken through the three steps of validation, as follows: "Data validity", "conceptual validity", and "operational validity". "Data validity" is used to prove that sufficient data (lists of disruptions, waste types, and lean tools) are utilized for the LCDMM creation. Such data lists were created based on the extensive literature review, as discussed above.

"Conceptual validity" aims to justify the theory underlying the LCDMM creating process, logic, and structure. Thus, the disruption abstraction process, particularly obtaining waste types of each disruption, was conducted by a focus group interview with industry experts. Then, the validated waste types were used in the lean technique abstraction process. This abstraction process is supported by providing a strong literature backing.

The third step of the validation procedure is "operational validation", which aims to verify whether the LCDMM output has the required accuracy for its intended purpose [120]. In the current study, "operational validation" was realized through the comparison of the solutions proposed in the LCDMM with existing practical solutions [121,122], which are discussed in the following sections.

6.10. LCDMM Application to Cases

The following two examples provide a better understanding of the LCDMM application in order to obtain lean techniques as solutions for the emerging disruptions.

Case 1

The process starts with the disruption observation and formulation, which is used as input data (see Figure 4). For the first example, the disruption "improper coordination between different construction trades" is elaborated (step A), which occurs when different trades are forced to work in the same area, which causes an improper sequencing of activities [123]. Therefore, a crew might be kept waiting for another crew to finish work in a particular area or to reorganise a space [5]. Unnecessary movement, such as locating and organizing materials, can also accompany this disruption [109]. Although, "unnecessary movement" (W4) can accompany the considered disruption; it is mostly observed as a consequence of another waste, "improper sequencing of activities" (W1). Thus, waste W4 is not in a priority to deal with. Regarding the "abstraction process" (Step B), the considered disruption abstraction is related to the manpower flow and contains two types of wastes, "improper sequencing of activities" and "waiting". Thus, the "disruption abstraction" would be represented in the form MP1 <Mp; W1, W2>. The "matching process" (Step C) is executed by utilizing the decision-making matrix (see Appendix B, Table A4), where each mentioned disruption waste is matched with the self-titled one in the matrix; as illustrated in the "waste" row, all intersections including "manpower flow" (Mp or W) are marked (see in Appendix B, Table A5, intersections coloured in green). Then, lean techniques that can overcome all identified examples of disruption waste— "optimal solutions"—should be revealed. In case there are no lean techniques that are able to overcome all waste examples, then combinations of lean techniques should be applied— "combined solutions". For the considered disruption "improper coordination between different construction trades", seven possible "optimal solutions" are obtained (green intersections with a red border): Last planner system (RV1), involving "takt time" planning (CT2); changing activities from sequential order to parallel order (CT4), multiskilling (SF1), involving Kanban (IT1), reducing interdependence of production units (IT2), and first run studies/"Plan-Do-Check-Adjust" (PDCA) (CI3). The right to select only one solution for implementation (refinement process—Step D) is left to project managers as they understand the environment and specificity of a particular construction project.

Case 2

Thomas and Sanvido [110] observed a loss in construction productivity because of the "late material delivery" disruption, which is considered as another example in the current research (see Figure 5, Step A). This disruption was accompanied by poor communication between the erector and the fabricator, consequently leading to a long waiting time. Regarding the "abstraction process" (Step B), the considered disruption abstraction is related to material flow and contains two types of waste, "waiting for information or resources" (W3) and "not taking advantage of collaboration with supplier" (W18). In such a case, the considered disruption abstraction is introduced in the form MT4 <Mt; W3, W18>. According to the "matching process" (Step C), all appropriate intersections are marked in a matrix (see in Appendix B, Table A5, intersections coloured in blue). There are three possible "optimal solutions" obtainable, as follows (Table A5, blue intersections with a red border): Last planner system (RV1), synchronizing and aligning (CR2), and supplier-managed inventories (CR3).

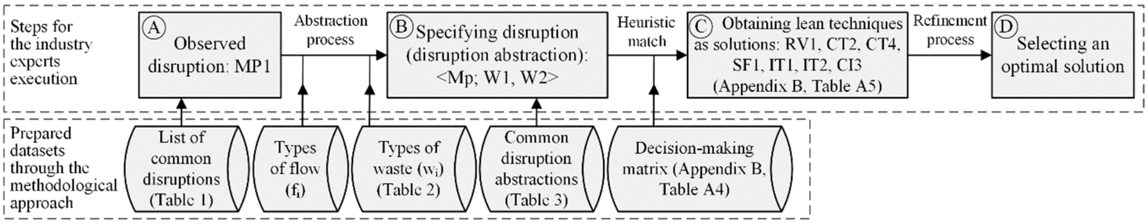

Figure 4. LCM application for the disruption "improper coordination between different construction trades".

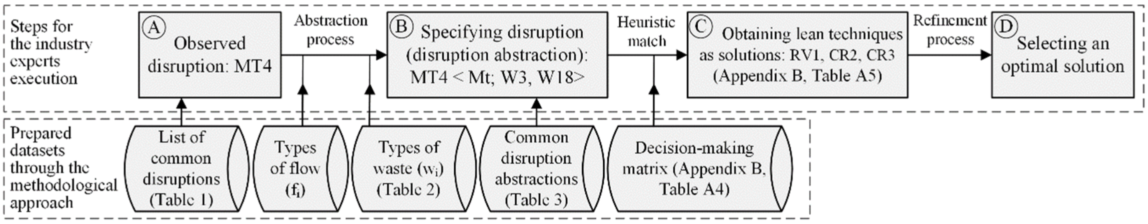

Figure 5. LCM application for disruption "late material delivery".

6.11. Existing Solutions Used for the Cases

Proposed lean techniques for the considered disruptions "improper coordination between different construction trades" and "late material delivery" were compared with the existing solutions in practice, which were found in the literature. Thus, Table 4 provides a summary of the proposed lean techniques (column 1 and 2) and the way each lean technique was implemented in practice to deal with the considered disruptions (column 3). The comparison shows that the use of the LCDMM gives useful lean tools as possible solutions. Such lean tools are generic in nature and require the use of creative analogies to transfer them into problem-specific solutions. This is an advantage of the proposed matrix, which is the ability to guide the problem solver towards the most effective solutions.

Table 4. Obtained lean techniques to prevent disruptions (refinement process).

LT Code	Proposed Lean Technique	Practical Applicability
1	2	3
	Disruption "Improper coordination between different construction trades"	
RV1	Last planner system	This refers to a "maturity index" as the state of work package readiness or a task to be executed [89]. In addition, weekly planning of activities and regular meetings can help to ensure crew timing and availability of corresponding resources [124,125].
CR2	Involving "takt time" planning	Frandson et al. [126] involved a "takt time" for exterior trade activities in one of the projects in Sacramento, California, which helped to increase productivity and complete the work ahead of schedule.
CT4	Changing activities from sequential order to parallel order	Sacks and Goldin [54] discuss decreasing cycle time of the finishing works in high-rise apartment buildings by involving multiskilling workers that can work in parallel rather than in a series by performing larger packages of continuous work.
SF1	Multiskilling	
IT1	Involving Kanban	Sacks et al. [88] propose a status board that is based on a "Kanban card". The first prototype was presented as a printed board then in a software format where status icons are placed by team leaders at the end of each day, and work signals are posted by managers later.
IT2	Reducing interdependence of production units	Dos Santos et al. [127] discuss solutions of a Brazilian construction company where a flow analysis was executed which recognises the micro and macro interdependencies present in the construction activities which are mostly represented as a sequential problem and have their origin in the design phase.
CI3	First Run Studies/ "Plan-Do-Check-Adjust" (PDCA)	This technique allows changes in crew composition and a better sequence of activities [61].
	Disruption "Late deliveries of materials"	
RV1	Last planner system	Barbosa et al. [19] describe a computer system developed by a team of Brazilian engineers involving a production planning and control technique (as a part of the "Last planner system") for the purpose of scheduling and tracking the activities of on-site forklifts in order to avoid machine idleness that consequently delays material delivery.
CR2	Synchronizing and aligning	Ala-Risku and Kärkkäinen [20] created the tracking software that provides visibility of material constraints through which suppliers can track the tasks on the near-term schedule and plan upcoming deliveries.
CR3	Supplier-managed inventories	

It is important to mention that managers can decide whether all types of assigned waste, which are proposed for common disruptions (see Table 4), are suitable for their specific case.

7. Conclusions

Maintaining a high level of construction productivity is one of the main goals of project managers, as a construction project's profitability critically depends on it. Enhancements in productivity would not be possible without identifying specific disruption problems, working toward to their elimination, and maintaining the improvements over time. "Lean construction" was introduced as an alternative management system in the current study, where numerous quoted authors demonstrated the implementation of various lean tools to mitigate construction productivity disruptions. However, the list of considered disruptions is limited in each of those studies and the choice of lean techniques to overcome them is not clearly justified. The current study illustrates the potential power of integrating "lean construction" and the "Clancey heuristic model" to elaborate a lean-Clancey-based decision-making matrix (LCDMM).

This matrix can benefit construction companies as a reusable tool for obtaining an optimal and beneficial solution for a particular productivity disruption's mitigation or elimination. In this case, a selection of appropriate lean techniques will not be limited by a project manager's knowledge and experience. Researchers in their turn can benefit by utilising the matrix to support their selection of lean tools to overcome various construction problems. Thus, the LCDMM, with its systematised lean techniques, will reduce redundant searching, reviewing, and analysing of the literature relevant to "lean construction" adaptation by scholars and practitioners whenever selecting solutions for productivity improvement is required. Two disruptions, "improper coordination between different construction trades" and "late deliveries of materials", were taken as examples to demonstrate the usefulness of the LCDMM. The proposed solutions were compared with the existing solutions in practice, which were found in the literature. This comparison illustrates that useful lean tools as possible solutions can be obtained through the developed LCDMM. The applicability of this research also allows for assembling the analysis of waste, where the abstraction process introduces ready-made waste analysis for common disruptions.

In the current stage of lean construction, it is probable that most companies and professionals are still on a learning curve. Thus, perhaps the adoption of the LCDMM should be made in small steps, such as the consideration of particular task disruption eliminations. After the matrix gains professional credibility, it can then be considered for more complex tasks.

This study involves constructive/design science research because it proposes a methodological approach to the interaction of two initiatives, lean construction and the Clancey heuristic model. Thus, this methodological approach can be adopted for other research areas where lean concepts can be applied to overcome various problems; however, this adaptation requires a reconsideration of methodological approach steps to meet the specifics of a particular study.

There are some limitations to this research. First, building construction projects or undertaking specific construction tasks (e.g., painting walls, installing fixtures) discussed in the literature review serve as a means to obtain disruptions and lean technique data and, accordingly, LCDMM development; thus, this matrix applicability for other types of projects (e.g., infrastructure, industrial buildings) requires additional adjustments to the methodological approach. Another point is that the proposed matrix needs to be approved in practice to validate outputs for various disruption combinations and whether those defined solutions are appropriate for the problems encountered.

Considering and obtaining lean techniques as solutions for more than three disruptions might require increased managerial effort while working with the LCDMM. In this regard, the "knowledge-based system" (KBS), as a software, may be used for systematising and standardising solution identification operations for a set of disruptions, which is the aim of further research. In addition, some of the proposed lean tools have a generic nature and require the use of creative analogies to transfer them into problem-specific solutions. Thus, the "knowledge-based system" (KBS) can also contain the ready-made solutions of lean technique implementation for easy use by industry experts.

Another prospective direction for further work can be the investigation of construction productivity through the consideration of critical success factors in risk management, where substantial work has been done in identifying the significant risks in the construction industry project [128] and BOT (Build-Operate-Transfer) projects [129], analysing risk factor data [130], and developing the methodology for concurrently identifying and analysing risks [131]. Thus, the lean philosophy can be integrated within the body of risk management in order to enhance construction productivity.

Author Contributions: Conceptualization, S.B. and X.Z.; methodology, S.B. and X.Z.; validation, S.B.; investigation, S.B.; writing—original draft preparation, S.B.; writing—review and editing, S.B.; supervision, X.Z.

Funding: This research was funded by the National Natural Science Foundation of China (Project Number: 71472052).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Structured Review Approach

Table A1. Results of structured review approach for extracting common disruptions.

		1st Step		2nd Step	3rd Step	
	Used keywords	Keyword searches	Applying filters (F1, F2, F3)	Paper content analysis	Papers' scientific significance assessment	Total
Scopus database	"construction productivity" and "labour productivity"	1614	910	52	52	78
	"cash flow" and "construction"	834	413	30	26	

Table A2. Results of structured review approach for extracting waste types and identify lean tools.

			1st Step		2nd Step	3rd Step
		Used keywords	Keyword searches	Applying filters (F1, F2, F3)	Paper content analysis	Papers' scientific significance assessment
Scopus database	Waste types	"lean", "lean philosophy" and "construction"	3013	2341	50	48
	Lean tools				105	105

Appendix B. Elaborating and Utilising LCDMM

Table A3. Lean principles and their techniques.

Lean Technique	Code	Lean Technique Description	Flow	Waste	References for Identified Flows and Waste
1	**2**	**3**	**4**	**5**	**6**
Reducing variability (Heijunka)					
Last planner system	RV1	Supports the timely realisation of plans by reducing delays, getting the work done in the best constructability sequence, matching manpower to available work, coordinating multiple interdependent activities, etc. [61,124,125].	Manpower flow	W1, W8	[18,20,108,118,124,125,132,133]
			Equipment and tools flow	W11, W24,	
			Material flow	W24	
			Information flow	W14	
			Workflow	W2, W3, W10, W18, W19, W21, W29	
Providing operational flexibility and responsiveness	RV2	Allows reactions to problems that induce variable conditions by providing sufficient resources when necessary [47,134].	Manpower flow	W8	[47,90]
			Material flow	W16	
Providing visual control and inspections	RV3	Refers to equipment and structure inspection by workers using raw human senses and any non-specialised inspection equipment to immediately recognise deviations from standards [28,61].	Workflow	W5, W27	[28,61,108]
Installing fail-safe (Poka-yoke) devices	RV4	Refers to automatic warning, identification and prevention of defects going to the next process [28,135].	Workflow	W5, W23	[61,108]
Preventative maintenance	RV5	Intended to keep all equipment in excellent working condition through proactive and preventative maintenance [47,136].	Equipment and tools flow	W5, W12	[47,136]
Reducing cycle time					
Batching	CT1	Refers to creating package sets needed to accomplish tasks and reduce work-in-process inventories [90].	Manpower flow Material flow Equipment and tools flow	W13, W15	[90]
			Information flow	W14	
Involving "takt time" planning	CT2	Aimed at making task duration consistent for every trade [126].	Manpower flow	W1, W2	[126]
Restructuring work	CT3	Refers to any work that should be performed ahead of its scheduled time [54].	Workflow	W2, W22	[54,137]
Changing activities from sequential order to parallel order	CT4	The number of work teams that can work in parallel rather than in series [54].	Manpower flow	W1, W2, W4	[54]

Table A3. *Cont.*

Lean Technique	Code	Lean Technique Description	Flow	Waste	References for Identified Flows and Waste
1	2	3	4	5	6
Simplifying by minimizing the number of steps, parts and linkages					
Multiskilling	SF1	Performing large packages of continuous work [54].	Manpower flow	W1	[54,137]
			Workflow	W2	
			Equipment and tools flow	W13	
Optimising components/structures and integrating more functionality into them	SF2	Reducing the part count of products through design changes or prefabricated parts [28].	Workflow	W22, W27	[28]
Standardising activities	SF3	Related to efficiently organising the sequence of job tasks that are repeatedly followed by a team member [138].	Manpower flow	W2, W4	[28,61,138]
Value Stream Mapping (VSM)	SF4	Decreasing activities that takes time, resources or space but does not add value [28].	Workflow	W2, W4, W25	[28,139]
Increasing process transparency					
Involving Kanban (Pull System)	IT1	Refers to the signals that make a process transparent and allow timely production in the required quantity [19,88].	Workflow	W2, W4	[19,88]
			Manpower flow	W1	
Reducing interdependence of production units	IT2	Allows correct timing and spacing between crews [61].	Manpower flow	W1, W2, W4	[127]
Increasing visualization	IT3	Refers to signs and labels around the construction site reminding workers about various issues [108].	Manpower flow	W5, W9	[108]
Making the process directly observable	IT4	Related to providing an observable machine layout and materials that allow an understanding of possible problems [127,140].	Material flow, Equipment and tools flow	W4	[68,127,140]
Using visual devices (Andon system or light board)	IT5	Related to a management tool that emphasises the visual status of operations (e.g., amount of machine operating), a quality or process problem via a signal alerting about abnormalities (e.g., quality problem, defective tools) [19].	Equipment and tools flow	W2, W3, W5	[140]
Incorporating information into the process	IT6	Related to inserting helpful workplace worker information [127].	Manpower flow, Information flow	W9	[127,140]
Involving Five S's	IT7	Refers to organizing an efficient, effective work space by identifying and storing items used, maintaining the area and sustaining the new order [108].	Material flow, Equipment and tools flow	W4, W13	[61,108,112]
Rendering invisible attributes visible through measurements	IT8	Reveals critical situations before they become problems [61].	Workflow	W10	[140]

Table A3. *Cont.*

Lean Technique	Code	Lean Technique Description	Flow	Waste	References for Identified Flows and Waste
1	**2**	**3**	**4**	**5**	**6**
Focusing control on the complete process					
Concurrent (simultaneous) engineering	CR1	Aimed at integrating all construction teams (e.g., general and specialty contractors, architects and design engineers) and integrating the construction and design stages [141].	Information flow	W14, W19, W26, W28	[141]
Synchronising and aligning	CR2	Aimed at synchronising delivery rate and sequence with installation rate and sequence [142].	Material flow	W3, W15, W18, W24, W28	[142]
Supplier-managed inventories	CR3	Applies when suppliers have access to inventory data and are responsible for maintaining inventory levels [143].	Material flow	W3, W15, W16, W18, W28	[20]
Establishing interpersonal communication	CR4	Aimed at using verbal and nonverbal exchange of information [144].	Manpower flow	W6, W7, W17	[144]
Showing respect	CR5	Intended as a means of showing appreciation for good worker ideas or qualities [114].	Manpower flow	W6	[114]
Deploying policy	CR6	Aimed at encouraging employees and giving them a common goal [145].	Manpower flow	W6	[145]
Building continuous improvement into the process (Kaizen)					
Involving creative thinking	CI1	Refers to reviewing problems or unorthodox solutions from a fresh perspective.	Workflow	W2, W10	[61,108,133]
Developing problem-solving skills	CI2	Refers to a way of considering a problem in detail in order to prevent its recurrence [61].	Workflow	W2, W10	[108,133]
First Run Studies/ "Plan-Do-Check-Adjust" (PDCA)	CI3	Aimed at reviewing work methods by redesigning and streamlining the different functions involved [108].	Manpower flow	W1	[108,133]
			Workflow	W2, W4, W20	
Brainstorming	CI4	Aimed at generating creative ideas and solutions through intensive group discussion [114].	Workflow	W2, W20, W21	[21]
Reengineering	CI5	Refers to the radical reconfiguration of processes and tasks to achieve dramatic improvements in performance measures such as cost, quality, service, and speed [17,28].	Workflow	W2, W25	[28]
Performance measurement					
Designing key performance indicators (KPIs)	BM1	Designed to eliminate inefficiency and maximize cost effectiveness and productivity [146,147].	Workflow	W2, W5, W10 W27, W28	[146–148]

Table A3. *Cont.*

Lean Technique	Code	Lean Technique Description	Flow	Waste	References for Identified Flows and Waste
1	2	3	4	5	6
Disruption index (DI)	BM2	Ratio calculated by the number of disrupted workdays divided by the total number of observed workdays [69,87].	Manpower flow	W1, W8, W9	[69,87]
			Equipment and tools flow	W11, W24	
			Material flow	W24	
			Workflow	W2, W3, W4, W5, W10, W13, W21, W22, W23, W25	
Project management index (PMI)	BM3	A dimensionless parameter that reflects the influence that the project management has on the cumulative labour performance [69,87].	Workflow	W2, W3, W10, W14, W19, W20	[69,87]
Performance ratio (PR)	BM4	A ratio calculated by the actual cumulative productivity divided by the expected baseline productivity (average values of baselines of all projects) [87].	Manpower flow	W1, W6–W9	[87]
			Equipment and tools flow	W11, W12, W24	
			Material flow	W24	
			Workflow	W2, W3, W4, W5, W10, W13 W21, W22, W23, W25	
Percent Plan Complete (PPC)	BM5	Calculated as the number of activities completed as planned divided by the total number of planned activities, which measures production planning effectiveness and workflow reliability [108,118,149,150]	Manpower flow	W1, W8	[18,108,112,118,132,149,150]
			Equipment and tools flow	W11, W24,	
			Material flow	W24	
			Information flow	W14	
			Workflow	W2, W3, W10, W18, W19, W21, W29	
Balanced scorecard (BSC)	BM6	A framework to understand the relationship between objectives, activities and results and integrate the management process [151]. Allow managers to look at their business performance from four important perspectives: financial, customer, internal business, and innovation and learning [118,152]	Workflow	W2, W3, W10, W14, W17, W18, W19, W28	[118,119,146,148,152,153]

Table A4. LCDMM.

Waste Code	Reduce Variability					Reduce the Cycle Time				Simplify				Increase Process Transparency								Focus Control on the Complete Process						Continuous Improvement					Benchmarking					
	RV1	**RV2**	**RV3**	**RV4**	**RV5**	**CT1**	**CT2**	**CT3**	**CT4**	**SF1**	**SF2**	**SF3**	**SF4**	**IT1**	**IT2**	**IT3**	**IT4**	**IT5**	**IT6**	**IT7**	**IT8**	**CR1**	**CR2**	**CR3**	**CR4**	**CR5**	**CR6**	**CI1**	**CI2**	**CI3**	**CI4**	**CI5**	**BM1**	**BM2**	**BM3**	**BM4**	**BM5**	**BM6**
W1	Mp						Mp		Mp	Mp				Mp	Mp															Mp				Mp		Mp	Mp	
W2	W						Mp	W	Mp	W		Mp	W	W	Mp			Eq										W	W	W	W	W	W	W	W	W	W	W
W3	W																	Eq					Mt	Mt										W	W	W	W	W
W4									Mp			Mp	W	W	Mp		Eq,Mt			Eq,Mt										W				W		W		
W5			W	W	Eq											Mp		Eq															W	W		W		
W6																									Mp	Mp	Mp									Mp		
W7																									Mp											Mp		
W8	Mp	Mp																																Mp		Mp	Mp	
W9																Mp			Mp, In															Mp		Mp		
W10	W																				W							W	W				W	W	W	W	W	W
W11	Eq																																	Eq		Eq	Eq	
W12					Eq																															Eq		
W13						Eq				Eq										Eq														W		W		
W14	In					In																In													W		In	W
W15						Mp,Mt,Eq																	Mt	Mt														
W16		Mt																						Mt														
W17																									Mp													W
W18	W																						Mt	Mt													W	W
W19	W																					In													W		W	W
W20																														W	W				W	W		
W21	W																																	W		W	W	
W22								W			W																							W		W		
W23				W																														W		W		
W24	Mt,Eq																						Mt											Mt,Eq		Mt,Eq	Mt,Eq	
W25													W																			W		W		W		
W26																						W																
W27			W								W																						W					
W28																						In	Mt	Mt									W					W
W29	W																																				W	

"Mp"—manpower flow, "Mt"—materials flow, "Eq"—Equipment and tools flow, "In"—information flow, "W"—workflow that may take values of "Mp", "Mt", "E", or "I".

Table A5. Obtaining lean techniques through the LCDMM (matching process).

Waste Code	**Reduce Variability**					**Reduce the Cycle Time**				**Simplify**				**Increase Process Transparency**								**Focus Control on the Complete Process**						**Continuous Improvement**				
	RV1	**RV2**	**RV3**	**RV4**	**RV5**	**CT1**	**CT2**	**CT3**	**CT4**	**SF1**	**SF2**	**SF3**	**SF4**	**IT1**	**IT2**	**IT3**	**IT4**	**IT5**	**IT6**	**IT7**	**IT8**	**CR1**	**CR2**	**CR3**	**CR4**	**CR5**	**CR6**	**CI1**	**CI2**	**CI3**	**CI4**	**CI5**
W1	Mp						Mp		Mp	Mp				Mp	Mp															Mp		
W2	W						Mp	W	Mp	W		Mp	W	W	Mp			Eq										W	W	W	W	W
W3	W																	Eq					Mt	Mt								
W18	W																						Mt	Mt								

"Green cells": "matching process" for the disruption "improper coordination between different construction trades" (Case 1); "Blue cells": "matching process" for the disruption "late material delivery" (Case 2); "red border": Indication of "optimal solutions".

References

1. El-Batreek, A.H.; Ezeldin, A.S.; Elbarkouky, M.M.G. A framework for construction labor productivity improvement in Egypt. In *AEI 2013: Building Solutions for Architectural Engineering*; ASCE: Reston, VA, USA, 2013; pp. 1007–1017.
2. Hanna, A.S.; Chang, C.-K.; Sullivan, K.T.; Lackney, J.A. Impact of shift work on labor productivity for labor intensive contractor. *J. Constr. Eng. Manag.* **2008**, *134*, 197–204. [CrossRef]
3. El-Gohary, K.M.; Aziz, R.F. Factors influencing construction labor productivity in Egypt. *J. Manag. Eng.* **2013**, *30*, 1–9. [CrossRef]
4. Jergeas, G. *Improving Construction Productivity on Alberta oil and Gas Capital Projects*; University of Calgary: Calgary, Canada, 2009.
5. Thomas, H.R.; Napolitan, C.L. Quantitative effects of construction changes on labor productivity. *J. Constr. Eng. Manag.* **1995**, *121*, 290–296. [CrossRef]
6. Thomas, H.R. Labor productivity and work sampling: The bottom line. *J. Constr. Eng. Manag.* **1991**, *117*, 423–444. [CrossRef]
7. Abd-El-Shakour, H. *Improving Productivity of Construction Projects Via Improving on-Site Construction Management*; Master Thesis, Zagazig University: Zagazig, Egypt, 1994.
8. Thomas, H.R. Effects of scheduled overtime on labor productivity. *J. Constr. Eng. Manag.* **1992**, *118*, 60–76. [CrossRef]
9. Thomas, H.R.; Yiakoumis, I. Factor model of construction productivity. *J. Constr. Eng. Manag.* **1987**, *113*, 623–639. [CrossRef]
10. Halligan, D.W.; Demsetz, L.A.; Brown, J.D.; Pace, C.B. Action-response model and loss of productivity in construction. *J. Constr. Eng. Manag.* **1994**, *120*, 47–64. [CrossRef]
11. Thomas, H.R.; Raynar, K.A. Scheduled overtime and labor productivity: Quantitative analysis. *J. Constr. Eng. Manag.* **1997**, *123*, 181–188. [CrossRef]
12. Ibbs, W.; Nguyen, L.D.; Lee, S. Quantified impacts of project change. *J. Prof. Issues Eng. Educ. Pract.* **2007**, *133*, 45–52. [CrossRef]
13. Abdel-Razek, R.H.; Hosny, A.; Alaraby, H. Improving bricklayers' productivity. In *the First Alexandria Conference on Structural and Geotechnical Engineering*; Alexandria University: Alexandria, Egypt, 1990; pp. 857–867.
14. Abdel-Razek, R.H. Measuring and improving construction productivity using work measurement techniques. In *the International Conference on Structural Engineering, Egyptian Society of Engineers and Canadian Society of Civil Engineering, Cairo, Egypt, 1992*; Ain Shams University: Cairo, Egypt, 1992; pp. 445–456.
15. Thomas, H.R.; Završki, I. *Theoretical Model for International Benchmarking of Labor Productivity*; Pennsylvania Transportation Institute, Pennsylvania State University: Pennsylvania, PA, USA, 1999.
16. Koskela, L.J.; Howell, G. The underlying theory of project management is obsolete. In *the PMI Research Conference*; University of Salford: Salford, UK, 2002; pp. 293–302.
17. Mao, X.; Zhang, X. Construction process reengineering by integrating lean principles and computer simulation techniques. *J. Constr. Eng. Manag.* **2008**, *134*, 371–381. [CrossRef]
18. AlSehaimi, A.O.; Tzortzopoulos, P.; Koskela, L. Last Planner System: Experiences from Pilot Implementation in the Middle East. In Proceedings of the 17th Annual Conference of the International Group for Lean Construction IGLC 17, Taipei, Taiwan, 15–17th July 2009; IGLC: Taipei, Taiwan.
19. Barbosa, G.; Andrade, F.; Biotto, C.; Mota, B. Heijunka system to level telescopic forklift activities using tablets in construction site. In Proceedings of the 21st Annual Conference of the International Group for Lean Construction (IGLC), Fortaleza, Brazil, 29 July–2 August 2013.
20. Ala-Risku, T.; Kärkkäinen, M. Material delivery problems in construction projects: A possible solution. *Int. J. Prod. Econ.* **2006**, *104*, 19–29. [CrossRef]
21. Ikuma, L.H.; Nahmens, I.; James, J. Use of safety and lean integrated kaizen to improve performance in modular homebuilding. *J. Constr. Eng. Manag.* **2010**, *137*, 551–560. [CrossRef]
22. Bernold, L.E.; AbouRizk, S.M. *Managing Performance in Construction*; John Wiley & Sons: Hoboken, NJ, USA, 2010; ISBN 0470919701.
23. Sanvido, V.E. Conceptual construction process model. *J. Constr. Eng. Manag.* **1988**, *114*, 294–310. [CrossRef]

24. Bröchner, J.; Olofsson, T. Construction productivity measures for innovation projects. *J. Constr. Eng. Manag.* **2011**, *138*, 670–677. [CrossRef]
25. Page, I.C. *Construction Industry Productivity: Study Report SR219*; BRANZ: Wellington, New Zealand, 2010.
26. Durdyev, S. *Pareto Analysis of on-Site Productivity Constraints and Improvement Techniques in New Zealand Building Industry: A Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Construction Management*; School of Engineering and and Advanced Technology, College of Sciences, Massey University at Albany Massey University: Wellington/Auckland, New Zealand, 2011.
27. Sanders, S.R.; Thomas, H.R. Factors affecting masonry-labor productivity. *J. Constr. Eng. Manag.* **1991**, *117*, 626–644. [CrossRef]
28. Koskela, L. *Application of the New Production Philosophy to Construction*; Stanford University: Stanford, CA, USA, 1992; Volume 72.
29. Alinaitwe, H.M.; Mwakali, J.A.; Hansson, B. Factors affecting the productivity of building craftsmen-studies of Uganda. *J. Civ. Eng. Manag.* **2007**, *13*, 169–176. [CrossRef]
30. Rivas, R.A.; Borcherding, J.D.; González, V.; Alarcón, L.F. Analysis of factors influencing productivity using craftsmen questionnaires: Case study in a Chilean construction company. *J. Constr. Eng. Manag.* **2010**, *137*, 312–320. [CrossRef]
31. Jarkas, A.M.; Bitar, C.G. Factors affecting construction labor productivity in Kuwait. *J. Constr. Eng. Manag.* **2011**, *138*, 811–820. [CrossRef]
32. Thomas, A.V.; Sudhakumar, J. Factors influencing construction labour productivity: An Indian case study. *J. Constr. Dev. Ctries.* **2014**, *19*, 53.
33. Durdyev, S.; Mbachu, J. Key constraints to labour productivity in residential building projects: Evidence from Cambodia. *Int. J. Constr. Manag.* **2018**, *18*, 385–393. [CrossRef]
34. Hanna, A.S.; Gunduz, M. Impact of change orders on small labor-intensive projects. *J. Constr. Eng. Manag.* **2004**, *130*, 726–733. [CrossRef]
35. Moselhi, O.; Assem, I.; El-Rayes, K. Change orders impact on labor productivity. *J. Constr. Eng. Manag.* **2005**, *131*, 354–359. [CrossRef]
36. Hanna, A.S.; Taylor, C.S.; Sullivan, K.T. Impact of extended overtime on construction labor productivity. *J. Constr. Eng. Manag.* **2005**, *131*, 734–739. [CrossRef]
37. Thomas, H.R.; Riley, D.R.; Sanvido, V.E. Loss of labor productivity due to delivery methods and weather. *J. Constr. Eng. Manag.* **1999**, *125*, 39–46. [CrossRef]
38. Srinavin, K.; Mohamed, S. Thermal environment and construction workers' productivity: Some evidence from Thailand. *Build. Environ.* **2003**, *38*, 339–345. [CrossRef]
39. Nasirzadeh, F.; Nojedehi, P. Dynamic modeling of labor productivity in construction projects. *Int. J. Proj. Manag.* **2013**, *31*, 903–911. [CrossRef]
40. Dai, J.; Goodrum, P.M.; Maloney, W.F.; Srinivasan, C. Latent structures of the factors affecting construction labor productivity. *J. Constr. Eng. Manag.* **2009**, *135*, 397–406. [CrossRef]
41. Liberda, M.; Ruwanpura, J.; Jergeas, G. Construction productivity improvement: A study of human, management and external issues. In *the Construction Research Congress: Wind of Change: Integration and Innovation*; ASCE: Honolulu, HI, USA, 2003; pp. 1–8.
42. Durdyev, S.; Ismail, S.; Bakar, N.A. Construction productivity in Turkmenistan: Survey of the constraining factors. *Int. J. e-Educ. e-Bus. e-Manag. e-Learn.* **2013**, *3*, 18. [CrossRef]
43. Chan, P.W.; Kaka, A. Productivity improvements: Understand the workforce perceptions of productivity first. *Pers. Rev.* **2007**, *36*, 564–584. [CrossRef]
44. Farrar, J.M.; AbouRizk, S.M.; Mao, X. Generic implementation of lean concepts in simulation models. *Lean Constr. J.* **2004**, *1*, 1–23.
45. Dunlop, P.; Smith, S.D. Planning, estimation and productivity in the lean concrete pour. *Eng. Constr. Archit. Manag.* **2004**, *11*, 55–64. [CrossRef]
46. Al-Sudairi, A.A. Evaluating the effect of construction process characteristics to the applicability of lean principles. *Constr. Innov.* **2007**, *7*, 99–121. [CrossRef]
47. Thomas, H.R.; Horman, M.J.; Minchin Jr, R.E.; Chen, D. Improving labor flow reliability for better productivity as lean construction principle. *J. Constr. Eng. Manag.* **2003**, *129*, 251–261. [CrossRef]

48. Bølviken, T.; Rooke, J.; Koskela, L. The Wastes of production in construction–A TFV based taxonomy. In *Proceedings of the 22nd Annual Conference of the International Group for Lean Construction*; Fagbokforlaget: Bergen, Norway, 2014; pp. 23–27. ISBN 978-82-321-0461-1.
49. Koskela, L. *An Exploration Towards A Production Theory and Its Application to Construction*; VTT Technical Research Centre of Finland: Espoo, Finland, 2000; ISBN 951385566X.
50. Shingo, S. *Study of 'Toyota' Production System from Industrial Viewpoint*; Productivity Press: New York, NY, USA, 1986.
51. Koskela, L. Making-do-the eighth category of waste. In Proceedings of the 12th Annual Conference of the International Group for Lean Construction, Helsingor, Denmark, 3–5 August 2004.
52. Serpell, A.; Venturi, A.; Contreras, J. Characterization of waste in building construction projects. In *3rd Annual Conference of the International Group for Lean Construction*; Howell, G., Ed.; University of New Mexico: Albuquerque, NM, USA, 1995; pp. 67–77.
53. Sullivan, W.G.; McDonald, T.N.; Van Aken, E.M. Equipment replacement decisions and lean manufacturing. *Robot. Comput. Integr. Manuf.* **2002**, *18*, 255–265. [CrossRef]
54. Sacks, R.; Goldin, M. Lean management model for construction of high-rise apartment buildings. *J. Constr. Eng. Manag.* **2007**, *133*, 374–384. [CrossRef]
55. Hosseini, S.A.A.; Nikakhtar, A.; Wong, K.Y.; Zavichi, A. Implementing Lean Construction Theory into Construction Processes' Waste Management. In *ICSDC 2011: Integrating Sustainability Practices in the Construction Industry*; ASCE: Kansas City, MI, USA, 2012; pp. 414–420.
56. Womack, J.P.; Jones, D.T. *Lean Thinking*; Simon and Schuster: New York, NY, USA, 1996.
57. Sarhan, S.; Pasquire, C.; King, A.; Manu, E. Institutional waste within the UK construction procurement context: A conceptual framework. *Eng. Proj. Organ. J.* **2018**, *8*, 36–64.
58. Sarhan, S.; Pasquire, C.; King, A. The concept of institutional waste within the construction industry: A potential theoretical framework. *Lean Constr. J.* **2017**, *2017*, 12–24.
59. Heim, J.; Compton, W.D. *Manufacturing Systems: Foundations of World-Class Practice*; National Academy of Engineering: Washington, DC, USA, 1992.
60. Womack, J.P.; Womack, J.P.; Jones, D.T.; Roos, D. *Machine that Changed the World*; Simon and Schuster: New York, NY, USA, 1990; ISBN 0892563508.
61. Salem, O.; Solomon, J.; Genaidy, A.; Minkarah, I. Lean construction: From theory to implementation. *J. Manag. Eng.* **2006**, *22*, 168–175. [CrossRef]
62. Shinohara, I. *NPS, New Production System: JIT Crossing Industry Boundaries*; Productivity Press: New York, NY, USA, 1988; ISBN 0915299216.
63. Monden, Y. *Toyota Production System: Practical Approach to Management*; Industrial Engineering and Management Press: Norcross, GA, USA, 1983.
64. De Magalhães, R.F.; Danilevicz, Â.D.M.F.; Saurin, T.A. Reducing construction waste: A study of urban infrastructure projects. *Waste Manag.* **2017**, *67*, 265–277. [CrossRef]
65. Lee, H.W.; Tommelein, I.D.; Ballard, G. Lean design management in an infrastructure design-build project: A case study. In Proceedings of the 18th Annual Conference of the International Group for Lean Construction, Haifa, Israel, 14–16 July 2010; pp. 14–16.
66. Mojtahedi, M.; Oo, B.L. The impact of stakeholder attributes on performance of disaster recovery projects: The case of transport infrastructure. *Int. J. Proj. Manag.* **2017**, *35*, 841–852. [CrossRef]
67. Mojtahedi, S.M.H.; Oo, B.L. Possibility of applying lean in post-disaster reconstruction: An evaluation study. In Proceedings of the 20th Annual Conference of the International Group for Lean Construction (IGLC 20), San Diego, CA, USA, 18–20 June 2012; Montezuma Publishing: San Diego, CA, USA.
68. Grau, D.; Caldas, C.H.; Haas, C.T.; Goodrum, P.M.; Gong, J. Assessing the impact of materials tracking technologies on construction craft productivity. *Autom. Constr.* **2009**, *18*, 903–911. [CrossRef]
69. Shehata, M.E.; El-Gohary, K.M. Towards improving construction labor productivity and projects' performance. *Alexandria Eng. J.* **2011**, *50*, 321–330. [CrossRef]
70. Nerwal, N.; Abdelhamid, T.S. Work structuring of construction crews: Installation of light fixtures. In Proceedings of the 18th Annual Conference of the International Group for Lean Construction, Haifa, Israel, 14–16 July 2010; pp. 316–325.
71. Clancey, W.J. Heuristic classification. *Artif. Intell.* **1985**, *27*, 289–350. [CrossRef]

72. Kahneman, D.; Egan, P. *Thinking, Fast and Slow*; Farrar, Straus and Giroux: New York, NY, USA, 2011; Volume 1.
73. Cui, Q.; Ward, M.; Rundensteiner, E.; Yang, J. Measuring data abstraction quality in multiresolution visualizations. *IEEE Trans. Vis. Comput. Graph.* **2006**, *12*, 709–716. [CrossRef] [PubMed]
74. Motta, E.; Lu, W. A library of components for classification problem solving. In Proceedings of the PKAW: The 2000 Pacific Rim Knowledge Acquisition, Sydney, Australia, 11–13 December 2000; pp. 11–13.
75. Bennett, J.; Creary, L.; Englemore, R.; Melosh, R. *Sacon: A Knowledge-Based Consultant for Structural Analysis*; Stanford University Calif Departmen of Computer Science: Stanford, CA, USA, 1978.
76. Rich, E. User modeling via stereotypes. *Cogn. Sci.* **1979**, *3*, 329–354. [CrossRef]
77. Fenves, S.J.; Maher, M. *Lou The Use of Artificial Intelligence Techniques in Preliminary Structural Design*; Carnegie Mellon Universit: Pittsburgh, PA, USA, 1981.
78. Brown, J.S. Pedagogical, natural language, and knowlege engineering techniques in SOPHIE I, II, and III. In *Intelligent Tutoring Systems*; Academic Press: New York, NY, USA, 1982.
79. van de Vijver, M.A.R. *Collaboration in Buyer-Supplier Relationships*; CentER, Tilburg University: Tilburg, The Netherlands, 2009; ISBN 9056682326.
80. Mohandes, S.R.; Zhang, X.; Mahdiyar, A. A comprehensive review on the application of artificial neural networks in building energy analysis. *Neurocomputing* **2019**, *340*, 55–75. [CrossRef]
81. Yi, H.; Wang, Y. Trend of the Research on Public Funded Projects. *Open Constr. Build. Technol. J.* **2013**, *7*, 51–62. [CrossRef]
82. Ansah, R.H.; Sorooshian, S. 4P delays in project management. *Eng. Constr. Archit. Manag.* **2018**, *25*, 62–76. [CrossRef]
83. Ensslin, L.; Ensslin, S.R.; Dutra, A.; Nunes, N.A.; Reis, C. BPM governance: A literature analysis of performance evaluation. *Bus. Process Manag. J.* **2017**, *23*, 71–86. [CrossRef]
84. Abbasian-Hosseini, S.A.; Nikakhtar, A.; Ghoddousi, P. Verification of lean construction benefits through simulation modeling: A case study of bricklaying process. *KSCE J. Civ. Eng.* **2014**, *18*, 1248–1260. [CrossRef]
85. Leung, M.; Yu, J.; Chan, Y.S. Focus group study to explore critical factors of public engagement process for mega development projects. *J. Constr. Eng. Manag.* **2013**, *140*, 4013061. [CrossRef]
86. Hallowell, M.R.; Gambatese, J.A. Qualitative research: Application of the Delphi method to CEM research. *J. Constr. Eng. Manag.* **2009**, *136*, 99–107. [CrossRef]
87. Abdel-Razek, R.H.; Abdel-Hamid, M. Labor productivity: Benchmarking and variability in Egyptian projects. *Int. J. Proj. Manag.* **2007**, *25*, 189–197. [CrossRef]
88. Sacks, R.; Treckmann, M.; Rozenfeld, O. Visualization of Work Flow to Support Lean Construction. *J. Constr. Eng. Manag.* **2009**, *135*, 1307–1315. [CrossRef]
89. Sacks, R.; Radosavljevic, M.; Barak, R. Requirements for building information modeling based lean production management systems for construction. *Autom. Constr.* **2010**, *19*, 641–655. [CrossRef]
90. Sacks, R.; Koskela, L.; Dave, B.A.; Owen, R. Interaction of lean and building information modeling in construction. *J. Constr. Eng. Manag.* **2010**, *136*, 968–980. [CrossRef]
91. Lim, E.C.; Alum, J. Construction productivity: Issues encountered by contractors in Singapore. *Int. J. Proj. Manag.* **1995**, *13*, 51–58. [CrossRef]
92. Rojas, E.M.; Aramvareekul, P. Labor productivity drivers and opportunities in the construction industry. *J. Manag. Eng.* **2003**, *19*, 78–82. [CrossRef]
93. Abdul Kadir, M.R.; Lee, W.P.; Jaafar, M.S.; Sapuan, S.M.; Ali, A.A.A. Factors affecting construction labour productivity for Malaysian residential projects. *Struct. Surv.* **2005**, *23*, 42–54. [CrossRef]
94. Enshassi, A.; Mohamed, S.; Mustafa, Z.A.; Mayer, P.E. Factors affecting labour productivity in building projects in the Gaza Strip. *J. Civ. Eng. Manag.* **2007**, *13*, 245–254. [CrossRef]
95. Makulsawatudom, A.; Emsley, M.; Sinthawanarong, K. Critical factors influencing construction productivity in Thailand. *J. KMITNB* **2004**, *14*, 1–6.
96. Abdul-Rahman, H.; Wang, C.; Takim, R.; Wong, S. Project schedule influenced by financial issues: Evidence in construction industry. *Sci. Res. Essays* **2011**, *6*, 205–212.
97. Abdul-Rahman, H.; Takim, R.; Min, W.S. Financial-related causes contributing to project delays. *J. Retail Leis. Prop.* **2009**, *8*, 225–238. [CrossRef]
98. Gardezi, S.S.S.; Manarvi, I.A.; Gardezi, S.J.S. Time extension factors in construction industry of Pakistan. *Procedia Eng.* **2014**, *77*, 196–204. [CrossRef]

99. Polat, G.; Ballard, G. Waste in Turkish construction: Need for lean construction techniques. In Proceedings of the 12th Annual Conference of the International Group for Lean Construction IGLC-12, Helsingør, Denmark, 3–5 August 2004; pp. 488–501.
100. Liu, S.-S.; Wang, C.-J. Resource-constrained construction project scheduling model for profit maximization considering cash flow. *Autom. Constr.* **2008**, *17*, 966–974. [CrossRef]
101. Horner, R.M.W.; Talhouni, B.T.; Thomas, H.R. Preliminary results of major labour productivity monitoring programme. In *3rd Yugoslavian Symposium on Construction Management*; University of Zagreb: Zagreb, Croatia, 1989; pp. 18–28.
102. Ghoddousi, P.; Hosseini, M.R. A survey of the factors affecting the productivity of construction projects in Iran. *Technol. Econ. Dev. Econ.* **2012**, *18*, 99–116. [CrossRef]
103. Kaming, P.F.; Olomolaiye, P.O.; Holt, G.D.; Harris, F.C. Factors influencing craftsmen's productivity in Indonesia. *Int. J. Proj. Manag.* **1997**, *15*, 21–30. [CrossRef]
104. Zakeri, M.; Olomolaiye, P.O.; Holt, G.D.; Harris, F.C. A survey of constraints on Iranian construction operatives' productivity. *Constr. Manag. Econ.* **1996**, *14*, 417–426. [CrossRef]
105. Durdyev, S.; Mbachu, J. On-site labour productivity of New Zealand construction industry: Key constraints and improvement measures. *Constr. Econ. Build.* **2011**, *11*, 18–33. [CrossRef]
106. Kaming, P.F.; Holt, G.D.; Kometa, S.T.; Olomolaiye, P.O. Severity diagnosis of productivity problems—A reliability analysis. *Int. J. Proj. Manag.* **1998**, *16*, 107–113. [CrossRef]
107. Aziz, R.F.; Hafez, S.M. Applying lean thinking in construction and performance improvement. *Alexandria Eng. J.* **2013**, *52*, 679–695. [CrossRef]
108. Salem, O.; Solomon, J.; Genaidy, A.; Luegring, M. Site implementation and assessment of lean construction techniques. *Lean Constr. J.* **2005**, *2*, 1–21.
109. Thomas, H.R.; Sanvido, V.E.; Sanders, S.R. Impact of material management on productivity—A case study. *J. Constr. Eng. Manag.* **1989**, *115*, 370–384. [CrossRef]
110. Thomas, H.R.; Sanvido, V.E. Role of the fabricator in labor productivity. *J. Constr. Eng. Manag.* **2000**, *126*, 358–365. [CrossRef]
111. Odeyinka, H.A.; Lowe, J.; Kaka, A. An evaluation of risk factors impacting construction cash flow forecast. *J. Financ. Manag. Prop. Constr.* **2008**, *13*, 5–17. [CrossRef]
112. Westö, V. *Last Planner System : Investigation of Possible Benefits From Implementing LPS in Ruukki Construction Building Systems*; Bachelor's Thesis, Yrkeshögskolan Novia: Vaasa, Finland, 2018.
113. Bertelsen, S.; Koskela, L. Construction beyond lean: A new understanding of construction management. In Proceedings of the 12th Annual Conference in the International Group for Lean Construction, Helsingør, Denmark, 3–5 August 2004.
114. Mayor, M. *Longman Dictionary of Contemporary English*; Longman: Harlow, UK, 2009; ISBN 1408202972.
115. Gupta, V.; Kansal, R. Improvement of construction labor productivity in Chambal region. *Int. J. Res. Eng. Technol.* **2014**, *3*, 34–37.
116. Hanna, A.S.; Russell, J.S.; Vandenberg, P.J. The impact of change orders on mechanical construction labour efficiency. *Constr. Manag. Econ.* **1999**, *17*, 721–730. [CrossRef]
117. Hwang, B.-G.; Thomas, S.R.; Haas, C.T.; Caldas, C.H. Measuring the impact of rework on construction cost performance. *J. Constr. Eng. Manag.* **2009**, *135*, 187–198. [CrossRef]
118. Sarhan, S.; Fox, A. Performance measurement in the UK construction industry and its role in supporting the application of lean construction concepts. *Australas. J. Constr. Econ. Build.* **2013**, *13*, 23–35. [CrossRef]
119. Kagioglou, M.; Cooper, R.; Aouad, G. Performance management in construction: A conceptual framework. *Constr. Manag. Econ.* **2001**, *19*, 85–95. [CrossRef]
120. Sargent, R.G. Validation and verification of simulation models. In Proceedings of the 2004 Winter Simulation Conference, Washington, DC, USA, 5–8 December 2004; Volume 1.
121. Mohamed, Y.; Abourizk, S.; Asce, M. Application of the Theory of Inventive Problem Solving in Tunnel Construction. *J. Constr. Eng. Manag.* **2005**, *131*, 1099–1108. [CrossRef]
122. Nassar, N.; AbouRizk, S. Introduction to Techniques for Resolving Project Performance Contradictions. *J. Constr. Eng. Manag.* **2016**, *142*, 4016027. [CrossRef]
123. Hanna, A.S.; Russell, J.S.; Nordheim, E.V.; Bruggink, M.J. Impact of change orders on labor efficiency for electrical construction. *J. Constr. Eng. Manag.* **1999**, *125*, 224–232. [CrossRef]

124. Ballard, G.; Howell, G. An update on last planner. In Proceedings of the 11th Annual Conference International Group for Lean Construction, Blacksburg, VA, USA, 22–24 July 2003.
125. Fiallo, M.; Revelo, V. Applying the last planner control system to a construction project: A case study in Quito, Ecuador. In Proceedings of the 10th Annual Conference of the International Group for Lean Construction, Gramado, Brazil, 6–8 August 2002.
126. Frandson, A.; Berghede, K.; Tommelein, I.D. Takt time planning for construction of exterior cladding. In Proceedings of the 21st Annual Conference of the International Group for Lean Construction, Fortaleza, Brazil, 29 July–2 August 2013.
127. Dos Santos, A.; Powell, J.; Sharp, J.; Formoso, C. Principle of transparency applied in construction. In Proceedings of the Annual Conference (IGLC-6), Guarujá, Brazil, 13–15 August 1998; pp. 16–23.
128. Ebrahimnejad, S.; Mousavi, S.M.; Mojtahedi, S.M.H. A model for risk evaluation in construction projects based on fuzzy MADM. In Proceedings of the 2008 4th IEEE International Conference on Management of Innovation and Technology, Bangkok, Thailand, NJ, USA, 21–24 September 2008; IEEE: Piscataway, NJ, USA; pp. 305–310.
129. Ebrahimnejad, S.; Mousavi, S.M.; Mojtahedi, S.M.H. A fuzzy BOT project risk evaluation model in iranian power plant industry. In Proceedings of the 2008 IEEE International Conference on Industrial Engineering and Engineering Management, Singapore, 8–11 December 2008; pp. 1038–1042.
130. Mojtahedi, S.M.H.; Mousavi, S.M.; Aminian, A. A non-parametric statistical approach for analyzing risk factor data in risk management process. *J. Appl. Sci.* **2009**, *9*, 113–120.
131. Mojtahedi, S.M.H.; Mousavi, S.M.; Makoui, A. Risk identification and analysis concurrently: Group Decision Making afpproach. In Proceedings of the 2008 4th IEEE International Conference on Management of Innovation and Technology, Bangkok, Thailand, 21–24 September 2008; pp. 299–304.
132. Hicham, H.; Taoufiq, C.; Aziz, S. Last planner system: Implementation in a moroccan construction project. In Proceedings of the 24th Annual Conference of the International Group for Lean Construction, Boston, MA, USA, 20–22 July 2016; pp. 193–202.
133. Walia, B.; Suri, N.M. Implementation of last planner system and challenges encountered in an Indian residential construction project. *Int. Res. J. Eng. Technol.* **2017**, *04*, 2881–2888.
134. Horman, M.; Kenley, R. Process dynamics: Identifying a strategy for the deployment of buffers in building projects. *Int. J. Logist. Res. Appl.* **1998**, *1*, 221–237. [CrossRef]
135. Shingo, S. *Zero Quality Control: Source Inspection and the Poka-Yoke System*; CRC Press: Boca Raton, FL, USA, 1986; ISBN 0915299070.
136. Alam, M.; Verma, A. Case Study on Implementation of TPM. *Imp. J. Interdiscip. Res.* **2016**, *2*, 2228–2237.
137. Yu, H.; Tweed, T.; Al-Hussein, M.; Nasseri, R. Development of lean model for house construction using value stream mapping. *J. Constr. Eng. Manag.* **2009**, *135*, 782–790. [CrossRef]
138. Blyth, K.; Lewis, J.; Kaka, A. Developing a framework for a standardized works programme for building projects. *Constr. Innov.* **2004**, *4*, 193–210. [CrossRef]
139. Kraemer, K.; Henrich, G.; Koskela, L.; Kagioglou, M. How construction flows have been understood in lean construction. In Proceedings of the 4th International SCRI Symposium, Salford, UK, 26–27 March 2007; The University of Salford: Salford, UK.
140. Tezel, A.; Koskela, L.J.; Tzortzopoulos-Fazenda, P.; Formoso, C.T.; Alves, T.; Neto, B.; Viana, D.; Mota, B. *Process Transparency on Construction Sites: Examples from Construction Companies in Brazil*; University of Huddersfield: Huddersfield, UK, 2010.
141. Ballard, G. Can pull techniques be used in design management? *CIB Rep.* **1999**, *26*, 149–160.
142. Howell, G.; Ballard, G. Implementing lean construction: Understanding and action. In Proceedings of the 6th Annual Conference of the International Group for Lean Construction, Guarujá, Brazil, 13–15 August 1998; IGLC: Guarujá, Brazil.
143. O'Farrell, P.N.; Wood, P.A. Formation of strategic alliances in business services: Towards a new client-oriented conceptual framework. *Serv. Ind. J.* **1999**, *19*, 133–151. [CrossRef]
144. Manning, J. A constitutive approach to interpersonal communication studies. *Commun. Stud.* **2014**, *65*, 432–440. [CrossRef]
145. Vyas, K.C. *Toyota Production System*; The University of Texas at Austin: Austin, TX, USA, 2011.

146. Hatzigeorgiou, A.; Manoliadis, O. Assessment of Performance Measurement Frameworks Supporting the Implementation of Lean Construction. In Proceedings of the 25th Annual Conference of the International Group for Lean Construction, Heraklion, Greece, 9–12 July 2017; Volume II, IGLC: Heraklion, Greece, 2017; pp. 153–160.
147. Costa, D.B.; Formoso, C.T.; Kagioglou, M.; Alarcón, L.F.; Caldas, C.H. Benchmarking initiatives in the construction industry: Lessons learned and improvement opportunities. *J. Manag. Eng.* **2006**, *22*, 158–167. [CrossRef]
148. Bassioni, H.A.; Price, A.D.F.; Hassan, T.M. Performance measurement in construction. *J. Manag. Eng.* **2004**, *20*, 42–50. [CrossRef]
149. Ballard, G. Improving work flow reliability. In Proceedings of the 7th Annual Conference of the International Group for Lean Construction, Berkeley, California, USA, 26–28 July 1999; IGLC: Berkeley, CA, USA, 1999; pp. 275–286.
150. España, F.; Tsao, C.C.Y.; Hauser, M. Driving continuous improvement by developing and leveraging lean key performance indicators. In *20th Annual Conference of the International Group for Lean Construction*; Montezuma Publishing: San Diego, CA, USA; Volume 20.
151. Beatham, S.; Anumba, C.; Thorpe, T.; Hedges, I. KPIs: A critical appraisal of their use in construction. *Benchmarking Int. J.* **2004**, *11*, 93–117. [CrossRef]
152. Mohamed, S. Scorecard approach to benchmarking organizational safety culture in construction. *J. Constr. Eng. Manag.* **2003**, *129*, 80–88. [CrossRef]
153. Kaplan, R.S.; Norton, D.P. Strategic learning & the balanced scorecard. *Strateg. Leadersh.* **1996**, *24*, 18–24.