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Human–Robot Collaboration and Lean Waste Elimination: Conceptual Analogies and Practical Synergies in Industrialized Construction

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Abstract: The presence of robots in industrial environments is a well-established reality in Industry 4.0 and an absolute necessity in Industry 5.0, with human–robot collaboration (HRC) at the paradigm's core. Concurrently, lean production remains one of the most influential production paradigms, which strives to eliminate Muda (non-value adding activities), Mura (unevenness), and Muri (people overburdening). However, what conceptual analogies and practical synergies are there between the lean production paradigm and HRC, and how do other Industry 4.0 technologies support this interaction? This research aims to answer this question in the context of industrialized construction, an ideal implementation field for both those approaches. The constructive research methodology is used to showcase, through evidence from the literature, that HRC aimed at the improvement of ergonomics, safety and efficiency has a positive contribution towards the elimination of all the lean wastes, while technologies like AR, VR, wearables, sensors, cloud computing, machine-learning techniques and simulation are crucially important for the intuitiveness of the collaboration between the human and the robotic partner. This is, to the author's best knowledge, the first attempt to systematically record the commonalities between Lean and HRC, thus enhancing the very limited construction literature related to HRC.

Keywords: Construction 4.0; constructive research; human–robot collaboration (HRC); Industry 4.0; Industry 5.0; industrialized construction; lean; offsite construction

1. Introduction

The Fourth Industrial Revolution, also referred to as "Industry 4.0", is a novel concept describing a disruptive innovation era in which organizations and processes are connected based on technology and interconnected devices, with the potential to reshape the value delivery mechanisms for services and products across the whole value chain [1]. The presence of robots in industrial environments is a well-established reality in the Fourth Industrial Revolution. However, traditional robotic systems are not suitable for every task. Depending on the required balance between the cognitive knowledge that only humans can provide and the speed, stamina, and physical strength that robots have to offer, an ideal co-working combination between humans and robots can be achieved. This combination seeks for both contributors to make best use of their own strengths and is called human–robot collaboration (HRC) [2]. According to [3], collaborative robotics is an umbrella term that conveys the general idea that proximity between machines and humans goes beyond the bare delimitation of spaces (or material flows or sequences) and results in some useful task. Examples of the "usefulness" could include cognitive and ergonomic benefits for machinery operators, improved flexibility of the organization of workflows, higher quality, and traceability of operations. HRC is also a prominent concept in the already emerging vision of Industry 5.0 [4], which places the wellbeing of the industry worker at the center of the production process.

Construction has long been adapting and incorporating knowledge, practices, and tools from the manufacturing sector, including the lean production system, value engineering exercises, and the 'Design for' approach [5]. In this context, the disruptive innovation of Industry 4.0 has also introduced the construction sector into an intelligent construction era, widely reported as Construction 4.0. In this context, topics such as robotic construction, artificial intelligence, or virtual reality are starting to penetrate the construction industry, making the limits between different scientific fields increasingly diffuse and transforming construction into an interdisciplinary industry [6].

However, despite the concept's popularity in the manufacturing sector, the implementation of robots in traditional construction is objectively difficult: unlike the manufacturing assembly line, tasks in construction are rarely connected in a consecutive chain, there are no standard construction plans as each product is unique, the resources experience frequent spatial-temporal conflicts, the plans are dynamically changing with a high degree of uncertainty, and the environment is harsh, often typified by noise, dust, mud and increased physical risks [7]. Hence, refs. [8] and [9] report that the great majority of robotic technologies still remain at an experimental stage, which puts them in the category of 'challenging' or (distantly) 'achievable'. Kim [10] also find that the current level of robotic reasoning, perception, and adaptability is not sufficient for complex and dynamic construction environments. In this context, robots are still among the least researched and least used areas of the ongoing technological transformation in the industry, despite the wide-ranging real and perceived benefits [11,12].

Nevertheless, construction also presents a non-traditional dimension which eliminates all the above-described restrictions and is thoroughly appropriate for the use of robotic technologies: offsite or industrialized construction, also known as prefabrication or volumetric or modular construction, which refers to the manufacturing of larger building components in a factory and their transportation to the construction site for assembly. The typical modular manufacturing line consists of a series of between 18 and 24 workstations, while the shape of the line varies (straight, U, L, etc.). Major framed sub-assemblies such as floors and roofs are fed to the early main line locations by off-line feeder workstations. Primary construction activities typically range between 40 and 60 activities, with each activity being performed by an independent team of workers on the line [13]. In this controlled 'factory' environment, the potential uses for robots are much more natural (e.g., [14–16]) and include robotic manufacturing and handling of brickwork, concrete components and panels, wooden panels and steel components, and the robotic assembly and finishing of modular blocks. The reported benefits include reduced project duration, higher quality, and improved health and safety [12,17]. Furthermore, as a result of the massively parallel nature of modular construction activities, multiple activity teams are expected to be working in the same module at the same time, while the same team may also have to concurrently juggle between several modules. Additionally, some activities are constrained to a single location because of equipment availability or facility limitations, while others, particularly those in interior finish, are far more flexible. Moreover, a varying degree of complexity will mean that more complex activities may span multiple workstations [13]. The aforementioned complexities call for optimal layout and worker management in operations and waste avoidance [18].

In the above context, the principles and techniques of lean production are necessary for the full potential of productivity and quality associated to the controlled environment of industrialized construction to be achieved [19]. The lean production paradigm, which originated in car manufacturing and specifically in Toyota to eliminate unnecessary effort and complexity, human errors, and quality defects, has been synonymous with the industry's quest for improvement since the early 1990s [20]. Its counterpart in the field of construction, i.e., lean construction, is an amalgamation of a contextual production model emerging from attempts to solve construction-specific problems by means of generic lean production principles, methods, and tools [21]. Lean construction has been constantly attracting the interest of academics since the 1990s and still has a remarkably strong presence in the literature

(e.g., [22–25]), which places it among the most influential paradigms in the construction management research. Despite the aforementioned popularity of the lean paradigm, its interactions with the use of robotic applications have so far received minimal attention in the construction management literature e.g., [26]. Furthermore, while HRC is in the core of the already emerging vision of Industry 5.0, there is no previous study systematically highlighting the analogies and synergies between HRC and lean construction towards waste elimination in the field of construction.

Therefore, this paper aimed to fill this gap and address the following questions:

- What commonalities are there between the lean production paradigm and HRC?
- How do HRC and lean construction interact in industrialized construction practices?
- How do other Industry 4.0 technologies support this interaction?

The remaining of the paper is organized as follows: Section 2 includes the theoretical background of this study, i.e., the basics of lean production and lean construction. Then, Section 3 presents a review of the literature related to the interaction of lean construction and Industry 4.0 technologies with special emphasis on robotics. Section 4 presents the methodology adopted and details the process and related choices step by step. Section 5 presents the literature evidence for demystifying the analogies between lean construction and HRC and shows how HRC interacts with waste generation mechanisms in the field of industrialized construction. Section 6 discusses the findings of this research in the context of the very limited relevant literature and particularly emphasizes the connections between the lean–HRC construct and the Industry 5.0 paradigm. Finally, Section 7 summarizes the conclusions of the research.

2. Theoretical Background

Lean production, also known as the Toyota Production System (TPS), means doing more with less—less time, less space, less human effort, less machinery, less material—while giving customers what they want, when they want it [27]. Lean production originated in the Japanese automotive industry in the 1950s and has been a tremendously influential paradigm conceptualized at various levels (continuous improvement philosophy, guiding principles, underlying practices/tools intended to achieve process improvement etc.). Its core target is to remove Muda (7 + 1 wastes), Muri (overburden), and Mura (unevenness/variability) from the processes. The seven Muda (wastes) were originally defined by Taiichi Ohno as transportation, (excess) inventory, motion, waiting, over-production, over-processing, and defects, and later were expanded to also include 'skills', or wasted human talent and ideas. However, eliminating Muda only represents one-third of the equation for making lean successful. The root problem is Mura (unevenness/variability), as variability can induce fluctuating and unexpected conditions, making objectives unstable and obscuring the means to achieve them [28,29]. Furthermore, variability causes people and machines overburdening (Muri), which in turn generates other waste [29]. In this context, lean thinking entails a continuous quest for stable and reliable processes, inextricably linked to standardization and standard work, which is one of the pillars of TPS. Furthermore, standard procedures are the only way for ensuring the processes' consistency, quality, and continuous improvement. One must standardize, and thus stabilize the process, before being able to improve it [30]. In addition, standard work in lean represents the safest, easiest, and most effective way of doing the job that we currently know; it is inextricably linked with ergonomics and, for example, entails proper posture and hand position visual guidelines in the workstations [27].

Lean first emerged in the construction industry with Koskela's discussion [31] on the value proposition of what he termed as "the new production philosophy". In this work, Koskela summarized lean thinking for construction into eleven principles fully aligned to the manufacturing paradigm and introduced the concept of flow in construction. His perspective was that the various flows (i.e., previous work, space, crew, equipment, information, materials, and external conditions such as the weather) have been historically neglected in construction, and as a result, the sector demonstrates complex, uncertain,

and confused flow processes with a significant amount of waste (non value-adding activities) [32,33]. This point is, according to [34], probably the most important contribution to the understanding of the construction process made by lean construction.

Around the same time, the report 'Rethinking Construction' by the UK's Construction Task Force, also widely referred to as 'the Egan Report' [35], popularized the "lean" label among construction professionals and positioned lean construction at the core of the industry's improvement initiatives [20]. Furthermore, the concept of 'Lean Thinking', the generic term used to describe application of the lean paradigm beyond manufacturing, was introduced by Womack and Jones in their bestselling book [36], which created conferences and a community around the topic of lean thinking. However, the ideas comprising the theoretical framework of lean thinking were a stark and to some extent imprecise simplification of the underlying theoretical framework of the Toyota Production System [37]. This resulted in the lean construction literature developing an 'interpretative flexibility' ranging from a narrow, operational project-level point of view focused on waste elimination to a holistic perspective of the industry with deep implications for the organizational practice, structure, supply chain management, and human resources [20]. As a result, some lean construction tools were uniquely developed for construction, while other manufacturing-based tools are being used in a different context/purpose compared to the original ones [38]. For instance, the Last Planner System for production control by Ballard [39] is a tool with significant industrial penetration—often considered synonymous with lean construction [20]—and has been exclusively developed in the context of lean construction. The same applies to the integrated project delivery approach by Matthews and Howell [40] as well as the target value delivery by Ballard [41], which are both inextricably linked to lean construction.

In this context, Bertelsen in [34] highlights the risk for lean production to be over-extended to construction and further comments that industrialized construction should not be considered part of lean construction as it conceptually belongs to lean production. In [21], Koskela agrees with the previous view, noting that lean production is biased towards manufacturing in stable factory conditions by a permanent organization: a condition which traditional construction clearly does not fulfill. Ballard and Howell [42] also confirm this perspective, supporting the view that the part of construction that actually belongs to contemporary product manufacturing should be claimed from construction, which is a dynamic system, in contrast to prefabrication. Given the above, this research conceptually places itself in the context of lean production and not lean construction.

3. Literature Review

The interaction of Lean and Industry 4.0 paradigms is a very well-researched topic. The scale of the relevant research interest in the recent years is reflected in hundreds of relevant publications in the past few years, indicatively including analyses on conceptual similarities (e.g., [43–46]), systematic reviews of the relevant literature (e.g., [47–50]), studies on implementation barriers and challenges [51,52], and critical success factors [53]. Lean methods are generally considered as enablers for Industry 4.0 implementation, and conversely, Industry 4.0 as a means to realize the extended lean enterprise [54]. Mayr et al. [55] argue that Lean and Industry 4.0 complement each other on a conceptual level with the main points of convergence being the reduction of complexity, the holistic approach and the pivotal role of employees. Bokhorst et al. [56] reinforce the above points by concluding that lean principles constitute a necessary condition for the efficient application of smart technologies in every operational context, while the opposite is not an equally strong requirement.

In this context, terms like Lean 4.0, lean automation, smart lean manufacturing, and Lean Industry 4.0 have also emerged, and a vast part of the literature contemplates how the combined use of specific Industry 4.0 and lean tools can improve operational efficiency in the context of manufacturing. Nevertheless, as certain Industry 4.0 technologies will support lean better than others, a clear understanding of how technology can support lean efforts is needed, or else it may become a type of waste in its own right [57]. To

address this, ref. [58] provided an extensive analysis of the interactions between 9 Industry 4.0 technologies and 14 lean manufacturing practices, and in this context, they identified 24 pairs with high synergistic relationships where cyber–physical systems (CPS) and Internet of Things (IoT) have the highest contribution. Other research in the same field includes, for example, the work by [59], who demonstrated how e-Kanbans supported by CPS-based real time data enable automatic orders and inventory level control. Furthermore, ref. [60] presented a production system which, assisted by the radio frequency identification (RFID) technology, can collect information about inventory, location, networking, and man–machine interfaces and enable digitized information sharing between shop floors and business departments. In addition, a similar mechanism based on sensors was proposed by [61] to recognize failures and automatically trigger fault-repair actions on other CPS. In the field of IoT and Cloud, ref. [62] proposed an IoT/IIoT based logistics model with Lean Six Sigma elements that enables the flow of real-time data to optimize processes, reduce costs, and resource consumption. Additionally, ref. [55] highlighted how cloud computing and machine-learning-based condition monitoring enhance product quality and total productive maintenance (TPM). Furthermore, ref. [63] discussed value-stream mapping (VSM) 4.0 as a new data-centered approach for achieving maximum waste reduction and appreciation of how information flows within the logistic processes. Similarly, ref. [64] supported the potential use of data analytics, simulation, and an RFID-supported user interface for improving the VSM with real-time result visualization.

In the field of industrialized construction, the adoption of automated processes has been associated with quality and productivity benefits resulting from reductions in time, cost, and human error in line with what the lean principles—inherent to offsite construction—seek to achieve [26,34]. In this context, industrialized construction provides the ideal environment, a factory, to fully apply lean principles and automation, with manufacturing robotic systems being particularly appropriate for use [26]. The relevance between lean and robotics is further confirmed by Pan and Pan [12], who investigated the determinants of adoption of robotics in offsite construction based on four case studies. Their findings reveal that a fair share of the factors emerging as critical for the adoption of robotics are closely relevant/directly affected by the implementation of lean principles. Specifically, they found that the adoption of robotics is mostly triggered by the perceived cost reduction and improvement in productivity, quality, accuracy, and safety, all of which are also among the targets of lean. Furthermore, they found that when the top management supports the vision of continuous improvement, which is synonymous to lean, then the adoption of robotics is easier. Similarly, the short delivery time requirement, which is part of any lean system's mission, was also placed in the list of factors driving robotics adoption. In addition, the complicated architectural and structural requirements of products were found to be potential barriers, meaning that simplification of the design, inherent to lean, is a critical factor for the successful use of robots in offsite construction. Finally, increased standardization, also inherent to lean, was listed among the factors positively influencing the adoption of robots in offsite construction. Therefore, it can be concluded that the use of robotics is far more likely to be successfully adopted in the context of a lean factory. Moreover, ref. [65] confirmed through an experimental process the beneficial impact of lean awareness in the efficient integration of a collaborative robot (also known as a "cobot") in the workstation, while [57] specifically showed how the use of Industry 4.0 technologies in manufacturing practice contributes to waste elimination, conceptualizing lean on the basis of the eight lean wastes. Furthermore, the interactions between lean principles and automation technologies in offsite construction, including robotic systems, were specifically investigated by [26] based on evidence in the literature. They found that robots can contribute to the reduction of variability and cycle times, can increase flexibility and standardization, and can also contribute to the system's flow and value. Therefore, it can be concluded that the adoption of robots also enhances and supports the successful implementation of the lean production paradigm.

4. Research Methodology

Methodologically, this study is constructive research, i.e., an applied study for defining and solving problems or improving existing systems or their performance, with the overall goal of adding to the existing body of knowledge [66]. The paper proposes a conceptual view of the interactions between two transformative paradigms, HRC and lean production, while the analogies and synergies evidenced by the experimental and practical literature are intended to guide and stimulate further research. The same approach has been previously implemented by Sacks et al. [67,68], who developed a framework for assessing the interconnections of lean and BIM. Da Rocha et al. [69] noted that the constructive research approach is commonly applied in the context of lean, since it can be used to develop solutions that aim to solve practical problems while also providing a theoretical contribution. AlSehaimi et al. [70] advocate the value of the constructive research approach to construction management as a non-traditional way to develop different models or tools that do not describe an existing reality, but on the contrary, help to create a new reality. They highlight the superiority of this underused research approach for bridging the gap between theory and practice compared to typical research methods such as surveys and questionnaires. The same need for constructive research to support construction project management has also been highlighted by [66], who demonstrated how practical and innovative solutions, grounded by valid research instruments, can be developed and applied in practice through the approach.

According to Kasanen et al. [71] constructive research is composed of six steps: (1) identification of the problem with theoretical and practical relevance, (2) understanding of the issue to be researched, usually through literature review and empirical studies, (3) construction of the solution in the form of a physical device or model, (4) implementation and test of the proposed solution, (5) connections between the solution and theoretical developments, and (6) analysis of the scope of applicability of the solution.

- Steps 1 and 2: finding a practical, relevant problem that has research potential and obtaining a general, comprehensive understanding of the topic.

According to [66], in the constructive approach, specifying the research problem entails making initial theoretical connections to the literature in the form of an analysis of the state of the art, as described in the previous sections.

Given that the lean production paradigm and the use of robots have a mutually beneficial influence on each other [12,26,57], this research puts into perspective the exact mechanisms of interactions between HRC and lean in the field of industrialized construction. For this purpose, lean was conceptualized on the basis of the three kinds of waste (Muda, Mura, Muri) that it strives to eliminate, while HRC is represented by its goals of efficiency, ergonomics, and safety [72]. This approach is in line with the original, remains the most succinct way to conceptualize lean [29], and expands the approach adopted by [57], who only considered Muda. Furthermore, compared to the lean framework adopted by [26], the approach of the current research has the additional advantage of revealing with greater clarity the conceptual analogies between lean's and HRC's main missions. As far as the 7 + 1 Muda wastes are concerned, this research focuses on the wastes of motion, waiting, over-processing, and underused human skills, which are most affected by the use of collaborative robots in the assembly line. The wastes of overproduction, inventory, and transportation have not been included, as they relate to organizational aspects that are not directly affected by the arrangement of the assembly line.

- Step 3: Designing a new construct

The constructive approach requires that the design of a construct should be based on an in-depth interpretation and synthesis of the contextual literature review and the practicalities of the problems [66]. Therefore, a comprehensive literature review/research synthesis was conducted. This is a data collection approach that involves activities such as identifying, recording, understanding, meaning-making, and transmitting information [73]. As asserted by [74], conducting a literature review is equivalent to conducting a research

study, with the information that the literature reviewer collects representing the data. When the goal of the literature review is to inform primary research, as is the case in this study, the literature review represents an embedded study [73].

The strategies employed for the review of the literature were chosen to suit to the characteristics of the different themes involved. Specifically, for lean production, three books contemplating the Toyota Production System were selected to provide the conceptual basis used for this research, i.e., [27,29,30]. Books were preferred over journal publications, as journal papers from the field of construction tend to be flexibly interpreting the lean paradigm with a varying degree of adherence to its original manufacturing features, as previously explained.

As far as HRC and lean in offsite construction are concerned, relevant searches were conducted in Scopus with the use of suitable combinations of keywords such as Robotics, Human-Robot Collaboration, Lean, Lean 4.0, Industry 4.0, Construction 4.0, Ergonomics, Efficiency, Waste, Offsite Construction, Modular, Prefabrication, Precast, Industrialized construction. Various combinations of the above keywords were searched among titles, abstracts, and keywords of published papers, which returned thousands of relevant articles. To reduce the number of the articles, papers from out-of-scope fields/sources were excluded, while relevant sources from the construction research field were prioritized (e.g., Automation in Construction, ASCE Journal of Construction Engineering and Management, proceedings from conferences specifically devoted to automation and robotics in construction). Furthermore, the most recently published (after 2019) and most cited articles were reviewed with priority. This was a strategy to ensure that both the latest advancements and the most widely acknowledged studies were represented. Additionally, some research papers emerged from the literature reviews of other publications (backward snowball search) and from automatic suggestions made by the publishers' websites based on past citation trends. The review of the literature presented herein is by no means exhaustive, but it is sufficient to fulfill the purpose of this study, which was to shed light on the nature and practical side of the interactions accompanying the conceptual analogies between HRC and lean, as these emerge from the theoretical framework.

- Step 4: Demonstrating that the new construct works

According to [66], testing, justification, and validation can be empirical or theoretical, quantitative or qualitative, or both. This study further notes that the most appropriate method to test and improve a construct is via a pilot case study, but in most cases in the construction industry, this approach is not realistic because of the risks and costs involved. Hence, he suggests that an alternative triangulation-based approach be implemented, such as data source triangulation, in which the data are expected to remain the same in different contexts, investigator triangulation, in which the same phenomenon is examined by several investigators, and methodological triangulation, in which several approaches are utilized in order to increase confidence in the interpreted and synthesized concept. Kasanen et al. [71] postulate that the adequacy of the research is not affected by the practical aspect of validation, as the latter is difficult to achieve without the actual implementation of the construct. In this regard, ref. [57] confirmed that the maturity of the actual implementation of digital technologies—let alone HRC, which is mainly experimental—in lean organizations is not high enough for reliable quantitative research to be conducted. This is further confirmed by the quantitative data presented by [58], which makes clear that conceptual research is much more frequent than empirical research in the field of Industry 4.0 applications, while particularly in the field of robotics, empirical research is minimal. In this context, the current research draws on literature-based investigator and methodological triangulation to confirm that the pivotal goals of HRC (efficiency, ergonomics, and safety) have close analogies to the target of lean to eliminate Muda, Mura, and Muri, as presented in the following section. These analogies make it easier to trace the mechanisms of support between lean and HRC and track them with greater transparency by specifically linking HRC effects with the elimination of given wastes.

- Steps 5–6: Showing the connections between the solution and theoretical developments/examining the scope of applicability

Constructive research demands that the construct should add to the body of knowledge and that the theoretical contributions should be posited: its novelty and scope of application should be clearly stated [66]. The findings of this research contribute a theoretical view towards understanding the impact of HRC on lean waste generation mechanisms, which are are further discussed in connection to the Industry 4.0 paradigm and the emerging vision for Industry 5.0 and its goal to create human-centric, efficient, and sustainable industries. This is, to the author's best knowledge, the first study that specifically addresses the analogies and synergies between the lean paradigm and HRC in this context, and it also adds to the very limited literature addressing the interactions between automation and the lean paradigm in the field of construction.

5. Results and Analysis

This section presents the combined output of Steps 3 and 4 and describes the process of demystifying the interactions between lean and HRC in offsite construction.

5.1. Elimination of Muri: Enhancement of Ergonomics/Safety

Although industrialization relocates many field operations to a more controlled factory environment, the construction techniques involved in offsite construction share many similarities with those employed in traditional sites [75]. Most of the time, workers are compelled to repetitively perform the same activities; due to this, they may experience fatigue or repetitive strain injuries [76]. Forceful exertion and awkward body posture are also listed as common causes of work-related musculoskeletal disorders in industrialized construction, as process standardization intensifies muscular tension [77]. Gautam et al. [78] describe how the screwing of gypsum board panels is a repetitive and strenuous task, where the installer frequently experiences shoulder injuries resulting from holding the tools overhead and exerting force on screws. Another such example of a strenuous, repetitive task is that of drilling on concrete surfaces [79]. These examples show that ergonomic improvements are necessary in the field of industrial construction; both HRC and lean can respond to this need as described below.

The use of collaborative robotics for ergonomic purposes is a major solution for the prevention of injuries associated with repetitive and dangerous tasks and workplace redesign [72]. Gualtieri et al. [80] present an extensive review of the relevant literature. Furthermore, ref. [81] propose the use of virtual reality (VR) technology for the ergonomic comfort of collaborative workplace design solutions to be studied and optimized before their implementation in real workplaces. The use of VR is also relevant to cases where HRC needs a more intuitive approach, possibly involving frequent human intervention. One such case is when a robot is manipulating a large object (e.g., a building panel), as the moving object's trajectory needs to be assessed in terms of operator safety [82].

Similarly, the lean paradigm has inextricable links to ergonomics, as the latter is inherent to safety, quality, and standard work, which are all among lean's fundamental elements (Table 1). Poor safety is an unambiguous form of waste, as injuries are costly not only in terms of human suffering, but also in terms of compensation costs, lost time, and productivity [75]. Furthermore, previous studies have confirmed the positive contribution of lean to occupational accident reduction (e.g., [75,83]). In this context, there is no doubt that at the conceptual level, there is substantial overlap between the lean objective to eliminate Muri (overburdening people) and HRC's goal of ergonomic improvement (Table 1).

Table 1. Comparison of scope between lean's goal for Muri elimination and HRC's goal for improved ergonomics/safety.

Lean Objective: Elimination of Muri (Overburdening People) [27,30]	HRC Objective: Improvement of Ergonomics/Safety [14,72]
Muri is pushing a machine or person beyond natural limits and results in safety and quality problems.	Cobots are increasingly adopted in tasks involving repetitive motions to minimize MSDs, injuries provoked by poor ergonomics, reduce the operator's fatigue, and increment the overall level of comfort.
Muri means "hard to do" and can be caused by poor job design or ergonomics, poor part fit, inadequate tools or jigs, unclear specifications, etc.	Construction robots offer improved working conditions by removing workers from dangerous environments.
Clearly define the best way to perform each job action and the proper sequence. Poor ergonomic design negatively affects productivity and quality as well as safety.	

On the practical side, the contribution of HRC to construction ergonomics and overburdening avoidance has also been confirmed in the construction literature. Ikuma et al. [84] report substantial fatigue reduction following the involvement of a collaborative robot in the execution of overhead gypsum board screwing. Brosque et al. [79] reported a 98% reduction of strenuous work after the involvement of a mobile robot in the process of drilling on concrete surfaces. Furthermore, ref. [85] found that a glazing robot assisted by a human worker on a high-rise building achieved similar productivity to the workers, with a reduction in potential safety incidents.

This evidence leads to the conclusion that the involvement of collaborative robots in construction, potentially supported by technologies such as VR, can have a direct positive impact on the lean goal of Muri elimination. Similarly, repetitive/strenuous construction processes like screw driving, nut driving, part fitting, grinding, milling, and drilling, fall within HRC areas for future development [72], which demonstrates that there is ample space for the joint application of lean and HRC to benefit construction employee wellbeing.

5.2. Elimination of Mura: Enhancement of Efficiency

The goal of lean is to deliver the highest possible quality to the customer, at the lowest possible cost, with the shortest possible lead time. This is achieved through stable and repeatable yet flexible processes that represent the current standard, ensure product quality, and embed a culture of continuous improvement (Table 2). However, the concept of stability in physically demanding processes, such as construction, is challenging; human workers do not perform identical work cycles and can also get tired. On the other hand, a robot can always work with the same programmed efficiency [86]. For instance, ref. [79] compared robotic and manual drilling on the same site and confirmed the certainty of production rates with robot task reports. Furthermore, structured environments, such as off-site factories, present more favorable conditions for robot operation because the task trajectories are known and repeated and lack obstacles or human interference [14].

Table 2. Comparison of scope between lean's goal for Mura elimination and HRC's goal for improved efficiency.

Lean Objective: Elimination of Mura (Unevenness) [27,29,30]	HRC Objective: Enhancement of Efficiency [72]
Use stable, repeatable methods but try to build as much flexibility into the system as possible.	
Flexibility is needed for operators to easily adjust work cycles in response to demand changes.	Efficiency results from simultaneously obtaining the shortest production time, high quality of products, accuracy, and optimal flexibility in the industrial process
Standard work aims to create processes and procedures that are repeatable, reliable, and capable.	
Standardized work is key to building with quality and without defects and establishes the foundation for continuous improvement.	
The more that the production is leveled, the shorter the lead time and the less strain experienced by operators.	

Aside from stability, HRC can also enhance the flexibility of the system, in line with what the lean organizational paradigm postulates. Specifically, mobile robots can provide the opportunity to increase or decrease the number of workplaces and thus facilitate the creation by companies of configurations that change dynamically based on the current demand. The same mobile robots can also be used to transport all the components that the human workers need for each task [87]. Moreover, a mobile robot can be equipped with a cobot to create a collaborative mobile robot that can pick and transport components and then execute assembly tasks based on the same components [81]. Given that the goal of lean is to embed both stability and flexibility in production processes, the expedience of collaborative practices towards this is evident from the above. Furthermore, the fact that efficiency in the context of HRC is defined in relation to quality, short lead time, accuracy, and flexibility (Table 2) makes the conceptual analogy between the goals of Mura elimination (lean) and efficiency (HRC) even more evident.

Furthermore, lean tools like 5S (Sort, Straighten (orderliness), Shine (cleanliness), Standardize (create rules), Sustain (self-discipline)) and Total Productive Maintenance (TPM) can further support HRC's efficiency and success. Implementing 5S ensures that the work stand only has what is needed to carry out a pre-defined work task, everything has a specific place, and the work area is clean and inspected [86]. This is particularly important for HRC, because a robot performs a programmed sequence of movements and the tools and/or assembly parts need to be located in specific places for the robot to detect them. Similarly, human workers cannot do their work if they cannot find the components that they need [81,86]. Furthermore, the cleaning process (Shine) often acts as a form of inspection that exposes abnormal and pre-failure conditions that could hurt quality or cause machine failure [30]. Additionally, TPM including both proactive and preventive maintenance is extremely important in HRC, as it ensures that a robot is continuously ready for work [86]. Along the same lines, ref. [81] highlighted the importance of timely, regular, and thorough maintenance to ensure the continuity of operations, as well as the reliability and availability of the technologies, including mobile robots, cobots, AR, and VR devices. This reveals that there is extensive interaction and significant synergy potential between HRC and lean for achieving efficiency through the elimination of Mura.

5.3. Elimination of Muda (Motion, Waiting, Overprocessing): Enhancement of Efficiency

The wastes of Motion, Waiting, and Overprocessing represent time, effort, and resources spent with no value added, bad design of task sequences, and/or inefficient

standard operating procedures [88]. However, HRC can improve, shorten, and simplify processes and optimize the sequence of tasks, which means that there is an evident opportunity for waste, as perceived by the lean paradigm, to be eliminated through the involvement of robots (Table 3). This is also confirmed in the construction literature, e.g., by [79], who in their comparison between manual and robotic drilling, report a 10% time reduction and elimination of a 12 h period for cleaning that was no longer required. Additionally, ref. [89] also reported a 20% time savings for brick construction when a robotic partner was involved. Furthermore, ref. [90] notes that robotic tools have the potential to eliminate waste from construction assembly processes that lead to low efficiency, such as surveying and calibration.

Table 3. Comparison of scope between lean's goal to eliminate overprocessing, waiting, and unnecessary motion and HRC's goal of improved efficiency.

Lean Objective: Elimination of Muda [30]		HRC Objective: Enhancement of Efficiency [14,72]
Unnecessary motion	Any non-value-adding motions such as looking for, reaching for, or stacking parts, tools, etc., and walking, are forms of waste.	Efficiency refers to the improvement of the entire industrial process or simplification of the operator's actions to complete a task by scheduling activities or via optimal planning of worker and robot actions. Cobots are increasingly adopted to augment productivity by shortening a task time. Construction robots offer enhanced productivity compared to conventional labor.
Waiting	Waiting for a machine or the next processing step, tool, supply, part, etc., or lack of work because of stockouts, delays, equipment downtime etc., are forms of waste.	
Overprocessing	Overprocessing, i.e., undertaking unnecessary activities during a work process, is waste.	

Specifically, collaborative robots work on optimized trajectories that are designed to minimize the cycle time of a task and/or improve the quality and comfort of collaborative tasks. To this end, control systems like sensors are put in place to create new path configurations and allow for both the coordinated movement and operation of the cobot and the execution of a specific sequence of tasks timely and safely [81,91]. Furthermore, scheduling algorithms can be implemented to optimize HRC productivity and eliminate waiting times. A systematic overview of the relevant motion planning/scheduling and line balancing techniques, usually based on machine-learnfing applications such as optimization algorithms and the artificial neural networks, was conducted in [72]. As [2] notes, the learning mechanism is based on trial-and-error cycles that direct the embedded cost function towards decisions that return the lowest possible cost.

As far as the role of other Industry 4.0 technologies is concerned, the use of augmented reality (AR), VR, wearables, and sensors can significantly contribute to an optimally designed collaborative workplace and efficient assignment of tasks, taking advantage of the data collected from time-and-motion and ergonomic analyses. In addition, even in cases of limited information, simulation based on the assembly line's digital twin gives the opportunity to decision-makers to evaluate and compare the benefits of the technologies under investigation on a potentially infinite number of scenarios before the actual implementation [81].

5.4. Elimination of Muda (Defects): Enhancement of Efficiency

Defects have no place in the lean production paradigm; their elimination is jointly addressed by all lean tools, whose purpose is to deliver exactly what the customer wants at the time that they want it. These include standardized work, 5S, TPM, and creative

devices that make it nearly impossible for an operator to make an error (error-proofing devices/poka-yoke) (Table 4). As [30] notes, the role of standardized work is pivotal in defect elimination: whenever a defect is discovered, the first question asked is "Was standardized work followed?" If the worker is following the standardized work protocol and the defects still occur, then the standards need to be modified.

Table 4. Comparison of scope between lean's goal of defect elimination and HRC's goal of improved efficiency.

Lean Objective: Elimination of Defects [27,30]	HRC Objective: Enhancement of Efficiency [16,72,86]
Production of defective parts mean wasteful handling, time, and effort.	Construction robots offer improved quality via precise control of functions and operations and by allowing real-time monitoring (and recording) of the operation. Cobots offer higher speed, quality, and pinpoint accuracy. HRC may additionally involve defects due to program or communication errors between the human and the robot.
5S is a series of activities for eliminating wastes that contribute to errors, defects, and injuries.	
Standardized work is key to building with quality and without defects and establishes the foundation for continuous improvement.	
When a poka-yoke detects an error, it should either shut down the machine or deliver a warning	
Poka-yokes reduce a worker's physical and mental burden by eliminating the need to constantly check for the common errors that lead to defects.	

Furthermore, in both manufacturing and industrialized construction, there is no doubt that automation invariably has a substantial positive effect on efficiency and quality. Bruckmann et al. [92] confirmed that one of the most attractive aspects of automated production is the opportunity to reduce costs while at the same time achieving a constantly high production quality. Nevertheless, when HRC is added in the picture, there is an additional risk for defects due to miscommunication between the human and the robot related to perception, decision-making, execution of motions, predictability of actions, and clarity of intentions [88] (Table 4). This shows that in order for HRC to efficiently serve lean's objective of defect elimination, the interaction intuitiveness between the human and the robotic partner must be optimized. This has also been highlighted by [93] as a condition for achieving efficiency in HRC.

To achieve this intuitiveness, ref. [94] claim that the presence and deployment of self-aware and self-healing sensors, machines, and workstations in assembly lines can prevent most problems and defects, while [72] presents four different state-of-the art modes (audio-based, touch-based, vision-based, and distance-based) that are often combined with VR/AR to reduce complexity and make interfaces more intuitive and readable by non-expert users. Stadnicka and Antonelli [86] see an analogy between poka-yoke solutions and sensors capable of detecting human movement and stopping the robot to avoid collisions. Dolgui et al. [81] note that the collection of information on these errors allows for the creation of databases for future reference and avoidance of similar situations, while [86] highlight the role of simulations towards this. Further, ref. [81] highlights the crucial importance of cloud computing for the efficient distribution of correct information and sharing across all the devices without physical connections. Sensorless solutions, often based on machine-learning techniques, have also been presented to overcome limitations induced by the presence of sensors (e.g., [95,96]).

This evidence shows that lean is the driving force in defect prevention, as the paradigm's overarching aim is to eliminate waste from the customer's perspective and its tools can support the efficient integration of the human and the robotic partner towards an efficient HRC. The human–robot interface that results from HRC is a source of potential risk for defects,

but the technological advancements of Industry 4.0 can efficiently mitigate it. Evidently, the more that the autonomy of the robotic partner increases and approaches full autonomy, the more that the risk of defects resulting from the human–robot interface will diminish.

5.5. Elimination of Muda (Unused Employee Creativity): Enhancement of Efficiency

The success of the lean paradigm is deeply founded on the engagement of all team members, especially those on the front lines. Suggestion programs are a main involvement activity for directly channelling problem-solving ideas to management. Furthermore, the involvement of operators for non-value-adding activities that do not need their input is considered disrespectful to the human mind [27]. In this sense, the replacement of human operators with robots for the execution of mundane tasks is an obvious enhancement of the lean objective for employee engagement with and utilization for worthwhile tasks (Table 5).

Table 5. Comparison of scope between lean's goal of elimination of underused skills and HRC's goal of improved efficiency.

Lean Objective: Elimination of Underused Employee Skills [30]	HRC Objective: Enhancement of Efficiency [9,72]
Losing time, ideas, skills, improvements, and learning opportunities by not engaging or listening to employees are forms of waste. Maintain and improve the skills that enable the production of added value The true value of continuous improvement is in creating an atmosphere of continuous learning. Train exceptional individuals and teams to work within the corporate philosophy to achieve exceptional results	Cobots are designed to focus on repetitive activities so that the operator can focus on problem-solving tasks. Using imitation learning methods, skilled human workers continually train construction robots and work with them to supervise their performance during the task execution.

Furthermore, the role of training is fundamental to the lean paradigm. Training must be the backbone of the management approach: from the moment they are hired into a company, employees go through a similar training regimen of learning-by-doing [30]. One can aptly observe that this is the exact same training paradigm highlighted in [9] as the future of robot use in construction (Table 5). Specifically, imitation learning or learning from demonstration enables human workers to transition their work profiles to those of demonstrators/supervisors and continue to serve essential roles in the performance of construction work. The advantage of such human–robot collaboration is the transfer of knowledge, whereby the robots uses mechanisms such as neural networks to acquire experience in human behavior, learn, and finally apply this knowledge to the task. Finally, the Industry 4.0 era is inextricably linked to training, as the introduction of the new technologies may require new frameworks or guides to enable an understanding of their use [81].

The above show that HRC supports lean's aspiration to develop operator skills and learning and to support their engagement in problem-solving and knowledge transfer processes. Additionally, HRC further enhances a culture of continuous improvement, as the operation of the robotic partners largely depends on machine-learning techniques which are based on continuous training.

6. Discussion

The pivotal goals of HRC for efficiency, ergonomics, and safety have close analogies to the target of lean to eliminate Muda, Mura and Muri, as shown. Robotics, in general, have previously been reviewed in the context of lean construction by Brissi et al. [26] and were associated with the reduction of variability, shorter cycle times, reduced inventories, reduced changeover times, improved control of production through leveling and standardization, and enhanced production flow due to simplification, reliable technology, and guaranteed capability. These findings are largely congruent with this paper's description

of the beneficial impact of HRC on the elimination of Mura (unevenness) and Muda (waste) of motion, waiting, over-processing, and defects. The main difference is the absence of the human factor found in the analysis in [26], meaning that there is no basis for confirming the findings related to Muri and human skill underuse. Similar research in the wider context of Industry 4.0 by Cifone et al. [57] also found that robots are among the most promising technologies for process improvement. They concluded that robotic applications contribute to the elimination of all Muda waste, with a greater effect on the prevention of defects, elimination of waiting times, optimization of motion, and avoidance of over-processing. As previously mentioned, this study also has a limited conceptual basis for lean that is restricted to Muda, with Muri and Mura being ignored. Similarly, from the ergonomic perspective alone, ref. [97] confirmed the positive impact of the collaborative workstation in terms of work performance and physical ergonomics in a manufacturing setting. They also highlighted the urgency of these work transformations for companies.

It should be noted though that lean production is a multi-layered paradigm that, along with its operational dimension, has an equally well-defined core of values where continuous improvement and respect for people stand out. In Toyota's philosophy, the worker is the most valuable resource; their safety, continuous training, and morale are top priorities [30]. Bicheno and Holweg [29] also add courage, creativity, consensus, responsibility, understanding, trust, and teamwork as integral parts of the Toyota value system. Dennis [27] highlights the fact that employee engagement, especially of those on the front lines where the real work gets done, is the key to continuous improvement. As previously explained, this aspect of lean, mainly reflected in Muri waste (people overburdening) as well as in the human skill underuse (Muda waste), has been underrepresented in the literature contemplating the interactions between lean and Industry 4.0. This is a major omission, especially in the light of the emerging vision of Industry 5.0, whose goal is to create a human-centric, efficient, and sustainable industry, able to provide a safe and inclusive working environment while striving for continuous worker up-skilling. A core feature in the Industry 5.0 vision is a collaborative work paradigm with human and robots sharing the same workspace and working together towards a common goal [4,98,99]. In other words, the fundamental difference between Industry 4.0 and Industry 5.0 is the emergence of HRC. Muller [100] notes that Industry 5.0 constitutes a paradigm shift where the use of technologies is primarily focused on supporting worker abilities instead of replacing them and leading to safer, more inclusive, and more satisfying working environments. Furthermore, the European Commission recently supported the Industry 5.0 vision as a forward-looking exercise that complements and extends the existing Industry 4.0 paradigm and addresses its weaknesses in the field of social sustainability [101].

In this context, the conceptual basis chosen to describe the multifaceted paradigm of lean (Muda–Mura–Muri) has proven to be very appropriate, as is the selection of HRC among all the concepts associated with Industry 4.0, given that both of these features of the current study allow for the effective positioning of lean not only in the Industry 4.0 context, but also in the Industry 5.0 vision. Furthermore, it clearly emerges that any future attempt by the construction industry to shift to a theoretical Construction 5.0 paradigm will require the sector to effectively incorporate not only robots, but also HRC. This, however, seems to be a very distant prospect, as despite the growing interest in robotic technologies in construction [10], robots are still among the least researched and least used of the ongoing technological transformations in the construction industry [11,12].

7. Conclusions

In the era of Industry 4.0, collaborative robots offering a safe, ergonomic, and efficient work environment is an established reality for the industrial production process. In construction, however, and despite robotic applications representing a growing research trend, robots are still among the least researched and least used of the ongoing technological transformations in the industry. Given that traditional construction is fundamentally different from manufacturing, the use of robots is much more relevant to industrialized

construction, where building components are individually designed, produced, and assembled in a controlled environment that is typically associated with quality and productivity gains. Furthermore, due to the complexity and high product standardization of offsite construction, the lean production paradigm is very well-placed to enhance operational efficiency while also creating beneficial synergies with Industry 4.0 technologies.

In this context, this study explored the interactions between HRC and lean in offsite construction and analyzed the conceptual analogies between lean's goal to eliminate people overburdening (Muri), unevenness (Mura), and waste (Muda) and HRC's goal to enhance ergonomics, safety, and efficiency. Furthermore, the following interactions were identified, using the constructive research approach, through evidence provided by the literature in both construction and manufacturing: First, HRC was found to provide a direct positive contribution to lean's objective of eliminating Muri (people overburdening) through the replacement of human operators with robots for strenuous, dangerous tasks. Second, a significant synergy potential between HRC and lean was established for the elimination of Mura (unevenness/variation) on the basis of the stability and flexibility afforded by their joint implementation. Third, HRC was found to provide a direct positive contribution to lean's objective of the elimination of motion, waiting, and over-processing waste through the employment of simulation exercises and optimization algorithms that allow for task shortening, simplification, and sequence optimization. Fourth, as far as the waste of defects is concerned, the human–robot HRC interface was identified as an additional source of potential error. The importance of technologies like AR, VR, wearables, sensors, and cloud computing was highlighted in this context to ensure the intuitiveness of the collaboration and avoidance of miscommunication. Finally, regarding the lean waste of underused human skills, it became clear how HRC contributes to its elimination by releasing human operators from mundane tasks and thus allowing human creativity to be used in training, problem-solving, and knowledge transfer processes. Furthermore, machine-learning techniques and related robot-training paradigms typifying efficient HRC, such as learning from demonstration, were established as factors able to embed the culture of continuous improvement that pervades the lean paradigm.

This is, to the best of the author's knowledge, the first study that specifically addresses the analogies and synergies between lean's three different kinds of wastes and HRC's goals and also adds to the very limited literature addressing the interactions between automation and the lean paradigm in the field of construction.

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