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Industry 4.0 Concepts and Lean Methods Mitigating Traditional Losses in Engineer-to-Order Manufacturing with Subsequent Assembly On-Site: A Framework

Felix Schulze[a]*, Patrick Dallasega[a]

[a]*Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100 Bolzano, Italy*

* Corresponding author. Tel.: +39-0471-017114; *E-mail address:* felix.schulze@natec.unibz.it

Abstract

Engineer-to-Order companies design and manufacture complex products based on specific customer requirements. Their project-driven processes and non-repetitive production causes various inefficiencies, which lead to productivity losses. Conventional approaches such as Lean Manufacturing and Lean Construction are limited in mitigating these losses due to their challenging implementation in the Engineer-to-Order environment. New concepts and technologies from Industry 4.0 have the potential to mitigate these losses through digitizing processes but are little researched in the Engineer-to-Order industry. This article classifies traditional losses from Engineer-to-Order manufacturing companies and through literature review identifies several Lean as well as Industry 4.0 methods that have the potential to mitigate these losses. The results are presented in a framework which can be used to develop a Lean and Industry 4.0 assessment tool for companies supporting the implementation of these concepts to mitigate the presented loss categories. Further research should focus on validating the framework with empirical data.

Keywords: : Industry 4.0; Engineer-to-Order (ETO); Lean Manufacturing; losses analysis; framework

1. Introduction

In an Engineer-to-Order (ETO) industry, the processes of design, engineering, project management, fabrication and on-site assembly are performed according to a specific customer order [1]. The high degree of customization, short lead-times, cost pressure and difficulty in planning and controlling operations lead to a high amount of non-value adding activities resulting in inefficiency and low productivity [2,3].

These losses in productivity due to inefficiencies along the complex business processes in ETO supply chains, forces companies to revisit their strategies and reconsider the adaption of proven methods and new technologies to improve productivity [4–6].

Several studies have been aimed at optimizing production processes in ETO environment using mainly general and typical Lean methods [4,5,7]. In this paper, we define Lean methods as Lean Manufacturing as well as Lean Construction which are both relevant practices in the ETO environment. They share numerous Lean methods which can be applied to the project-driven characteristics of ETO projects [8].

Lean methods have been firstly developed and applied in the automotive industry and progressively substituted traditional production methods [9–11]. The analysis of wastes, or non-value adding activities is a crucial component in Lean in order to continuously improve performance and increase customer value [12].

The challenges and barriers of implementing Lean methods in the non-repetitive environment of ETO enterprises [7]

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could be resolved by integrating technologies associated with Industry 4.0 [5,13] which could further improve already established Lean methods [14].

While Lean Manufacturing approaches have gained momentum as vital concepts in effectively reducing traditional losses in the ETO environment, less attention has been focused on Industry 4.0 concepts and technologies [3].

Industry 4.0 can be described as a fusion of concepts and technologies that blend the lines between physical, digital and biological functions [15,16]. In its analysis The Boston consulting group (BCG) divides Industry 4.0 into nine technology trends to transform the industrial production as well as the associated relationships among suppliers, producers, and customers [17]. These include: Big Data and Analytics, Autonomous Robots, Simulation, Horizontal and Vertical System Integration, Industrial Internet of Things, Cybersecurity, the Cloud, Additive Manufacturing and Augmented Reality. Concepts and technologies of Industry 4.0 have the potential to improve the ETO industry by enabling new and more efficient processes [7].

This paper aims to give the following contributions:

1) A classification of traditional losses in ETO manufacturing with subsequent assembly on-site;
2) A list of Lean methods and Industry 4.0 concepts and technologies identified for being suitable to mitigate the classified losses;
3) A framework that maps the Lean methods as well as the Industry 4.0 concepts and technologies according to the classified losses.

The remainder of the article is organized as follows. Related works are discussed in section 2. In section 3 the proposed framework is described, which classifies the application of Lean methods and Industry 4.0 concepts and technologies to mitigate the traditional losses. Section 4 provides the discussion and implications for future research. Finally, section 5 presents the conclusions.

2. Related works

Overall, the literature on Lean methods in the ETO industry is limited compared to that of volume or serial production systems [18]. Furthermore, to the best of our knowledge, an overview of suitable methods for reducing traditional losses in the ETO environment with assembly on-site is missing. Since losses and wastes significantly affect the productivity of Lean methods, their influence should be much more apparent in ETO literature [18–20].

Braglia et al. [19] analyze the hidden losses for manual assembly task activities proposing a novel indicator named Overall Task Effectiveness specifically suitable for ETO companies. Their proposed loss structure is suitable to analyze inefficiencies within manual assembly activities but does not consider other losses in further typical ETO processes such as Engineering, Project Management as well as Assembly on-site.

Axelsson et al. [21] present a model of how to use certain Lean and Industry 4.0 elements to reduce wastes specifically for road construction companies. Their system is also suitable to the general ETO environment but stays focused on the construction component while leaving out other ETO relevant functions.

Birkie and Trucco [18] show that Lean Manufacturing can be successfully implemented in ETO companies if waste creating activities are identified and eliminated, which is challenging due to the non-repetitive nature of manufacturing [7]. Complexity and dynamism factors that are categorized into internal (related to organizational personnel, function, level) and external (related to customers, suppliers, socio-political, competitors, and technology) result in a high uncertainty for ETO companies [18].

Strandhagen et al. [4] present typical wastes affecting lead time in an ETO case study and developed corresponding guidelines for companies on how to address each identified source of waste. The analyzed wastes of the main processes include amongst others: Sales (involvement of consultants, conversion of contract into product specification), Engineering (change order management, compatibility between CAD and ERP system), Procurement (timing and synchronization of procurement of long lead times), Production (synchronization of material supply and assembly process, assembly operations productivity) and Project Management (learning and experience transfer from finished projects, information sharing between company departments).

Based on findings from scientific literature, Gosling & Naim [20] and Birkie & Trucco [18] point out that more empirical research is required to prove the effects that Lean methods could have on efficiency of ETO operations, claiming evidence on the applicability of Lean in the ETO sphere is yet to be found.

Strandhagen et al. [4] indicate that further research should investigate how merging digital technologies can be applied to mitigate the analyzed sources of wastes.

Recently, the Industry 4.0 approach has gained momentum as a crucial method in further optimizing the Lean Manufacturing environment [7] but the aspect of digitization has not been yet sufficiently addressed [3].

Wagner et al. [22] as well as Pokorni et al. [23] focus on the impact of Industry 4.0 on Lean production systems for industrial companies. They show which Industry 4.0 technology has which kind of impact on Lean production principles and summarize their findings in a framework. Losses or wastes in the manufacturing industry and how either Lean or Industry 4.0 methods could mitigate them are not specifically discussed.

Another study by Mayr et al. [6] underlines the applicability of Lean and Industry 4.0 methods in a manufacturing environment by focusing on how various Industry 4.0 tools empower Lean methods. They point out that a holistic approach showing how to implement Industry 4.0 concepts with Lean Production methods is currently missing.

Even though the discussed studies indicate the facilitating effects of implementing Lean prior to an Industry 4.0 transformation [6,22], no study has examined this topic in detail [6,7].

Hence, the objective of this paper is to provide a structured framework identifying the Lean methods and Industry 4.0

concepts and technologies that mitigate the losses of ETO manufacturing with subsequent assembly on-site. Lean methods and Industry 4.0 share the same overall objectives of increased productivity and flexibility, albeit applying different approaches [6,24].

3. Framework

This chapter summarizes the traditional losses in ETO manufacturing with subsequent assembly on-site. A list of Lean methods and Industry 4.0 concepts and technologies applicable to mitigate these losses is presented and mapped in a framework according to the classified losses.

First, the different loss categories are explained in detail. Then the identified Lean methods are proposed followed by the identified Industry 4.0 concepts and technologies that can be applied in alleviating the detailed losses.

Generally, ETO products are highly customized, have complex structures with standardized and customized components and have strict time and budget constraints to fulfill the customers' requirements [25]. This complexity leads to various inefficiencies in the engineering, procurement, manufacturing, assembly and installation phases of a project [3]. Therefore, we propose a classification into six main categories: Losses caused by obstructions with Other Trades, Losses caused by the Customer, Losses caused by the Engineering department, Losses caused by the Project Management department, Losses caused by the Fabrication department as well as Losses caused directly by the Assembly On-Site. The review of scientific literature identifies multiple Lean methods as well as Industry 4.0 concepts and technologies, which can be applied to mitigate these ETO specific losses. Figure 1 summarizes the results.

3.1. Losses caused by obstructions with Other Trades

Losses caused by obstructions with Other Trades occur generally at the interfaces between various processes carried out by several trades, suppliers, and subcontractors. Examples include if the work of the upstream trade has not been performed according to specifications or the sharing of equipment is not scheduled properly.

Typical Lean Construction methods, such as *Location Based Management System* (*LBMS*), *Last Planner System* (*LPS*) and general *Pull Scheduling* are used to lessen these losses since they focus on forecasting activities in order to create a stable workflow and reduce risks and problem occurrence on the construction site [26,27].

LPS assists supervisors in scheduling across trades and processes thus addressing crucial interfaces between individual trades [28]. *LBMS* aims at maximizing continuous use of crews and equipment and thus adding to the LPS schedules in minimizing interruptions [29]. Olivierei and Seppänen (2018) could prove in a case study on three different residential tower projects that the obstruction of different trades involved in the construction project, mainly caused by following a CPM schedule, were successfully resolved by the use of *LBMS* without increasing the total construction duration [29]. Proper *Pull Scheduling* allows the general sequence of trades to be effectively coordinated [30].

The adoption of Industry 4.0 technologies is a consequent approach in further mitigating these inefficiencies. Industry 4.0 tools, such as *Web-Portals* based on Supply Chain Management and Information Integration through *Building Information Modeling* (*BIM*) aim to further mitigate these losses. *Portal systems* can be used for cross-organizational collaboration enabling for example a smooth coordination of equipment sharing and scheduling at the interfaces between different trades [31]. *BIM* serves as an information integration platform which allows all project stakeholders to attain and use the same up-to-date information [32].

3.2. Losses caused by the Customer

Losses caused by the customer comprise all the inefficiencies such as frequent changes of designs and specifications as well as delays because of missing approvals.

Lean methods that tackle these inefficiencies include *Integrated Project Delivery* (*IPD*), *Detailed Briefing* and *Concurrent Engineering*. *IPD* is a collaboration method, which involves the client throughout the complete phases of a project and thus accelerating decision-making [33]. *Detailed Briefing* engages the customer from the beginning of a project that helps to reduce misinterpretations and dissatisfaction among all project members [34]. *Concurrent Engineering* enables simultaneous processes for the design phase aiming at reducing the duration of engineering time and emphasizing customer satisfaction [35].

Consequently, Industry 4.0 tools can be utilized to cope with losses due to customer inefficiencies even more productively. *Cloud Computing* and *BIM* are Industry 4.0 practices that build on Lean methods to face these losses. *Cloud Computing* enables the involvement of all project actors including the client in all phases of the project without time lag to speed up decision making necessary for an uninterrupted project progress [36]. Singleton and Cormican (2013) have demonstrated on the fit-out of Terminal 2 in the Dubai Airport project that the use of CCT (Construction collaborative technologies) was vital to their success of the project. Based on *Cloud Computing* the specialist subcontractor as well as the customer were earlier involved in key decisions, which reduced the drawing revision cycles as well as produced fewer claims [36]. *BIM* is the fundamental tool to exchange information between the client and the project actors at various phases of the project [32].

3.3. Losses caused by the Engineering department

Losses caused by the Engineering department comprise all kinds of wastes caused by poor organization, planning and execution of complex and fragmented engineering tasks during the design phase. These include mistakes and discrepancies in design, technical documentation errors as well as delays in releasing drawings.

Proven Lean methods that try to improve these inefficiencies include *Concurrent Engineering*, *Value Based Management* (*VBM*), *Value Stream Mapping* (*VSM*), *Virtual Design Construction* (*VDC*), *Target Value Design* (*TVD*), *Design Structure Matrix* (*DSM*), as well as *Design Workshops*. These methods define a structured process how the engineering phase should be performed mitigating these inefficiencies.

Concurrent Engineering is used as a Lean method that allows parallel and collaborative construction and design, thus minimizing development time and maximizing throughput [37,38]. *VBM* and *VSM* are methods used at the beginning of the design phase to define value for the client and therefore reduce wastes and variability [39]. *VDC* is a design tool applied in the design phase for modeling and simulating, as well as to test for errors in design [40]. *TVD* is a management practice that is used to predict costs during a new product or design development. It helps to save time in the design process and reduce delays in the release of drawings by focusing on the target costs and requirements of the customer [33,41] *DSM* is used to analyze and rearrange the planned design processes in order to improve productivity, reduce design errors and prevent redundant design steps [35,41].

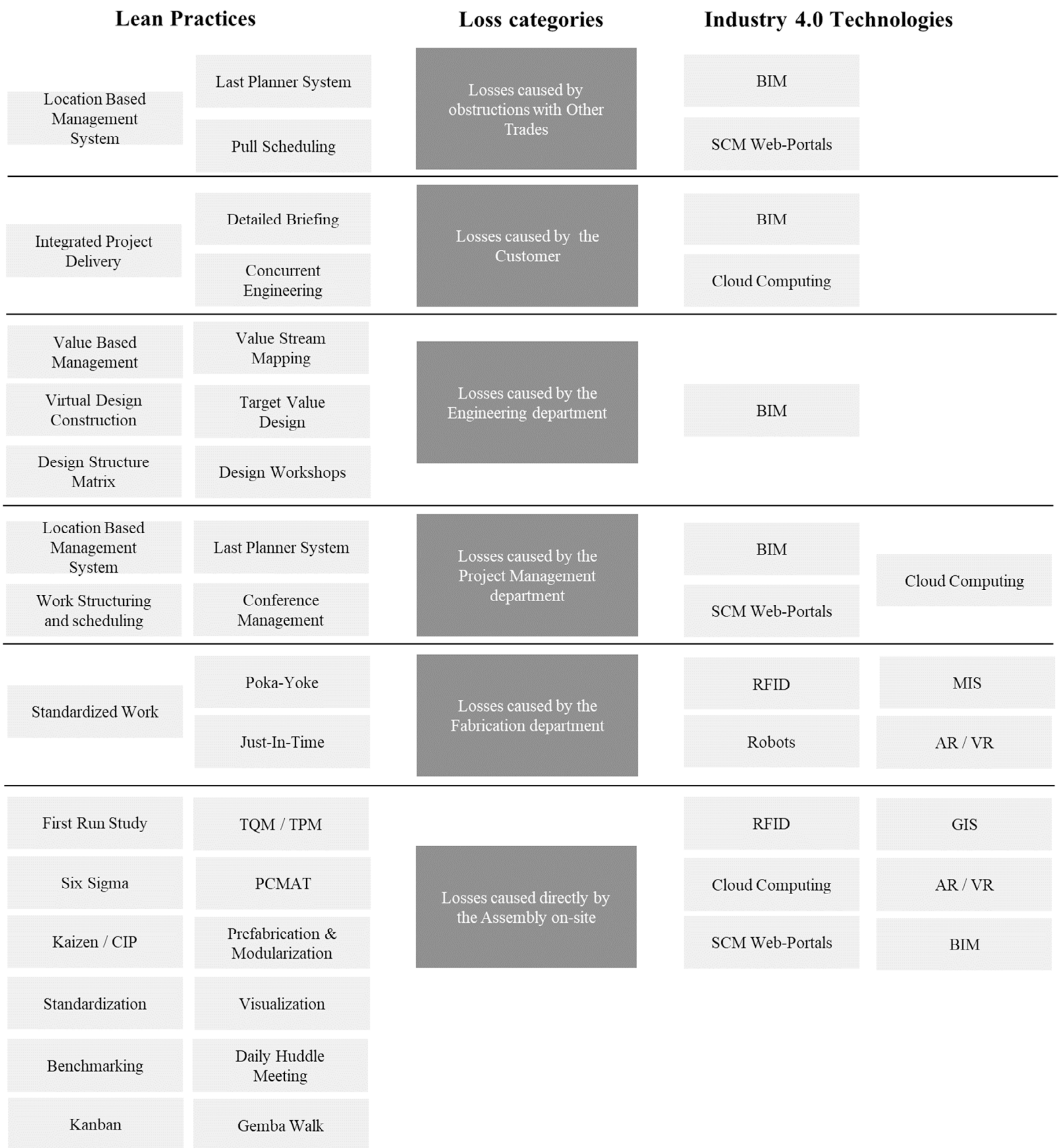

Figure 1: Framework mapping Lean methods and Industry 4.0 concepts and technologies according to the loss categories

BIM provides a platform which enables the design and sharing of information relevant for engineering, construction and operation of a building project over its entire life span [42,43]. In the design phase it can be used to build a 4D model to virtually simulate the process, construction and operation [42]. This helps to identify potential conflicts and analyze alternative solutions already in the design phase. Moreover, it increases communication and coordination between architects, engineers, contractors, and clients leading to better building designs and tenders, saving project time and improving cost estimations [44].

3.4. Losses caused by the Project Management department

Losses caused by the Project Management department entail all inefficiencies caused by a weak overall coordination of the project leading for example to unavailable material and equipment as well as a difficult accessibility on-site. Furthermore, not up-to-date schedules and wrong rating of reference values can be included here.

Classical Lean methods such as *Last Planner System* (*LPS*), *Location Based Management System* (*LBMS*), *Work Structuring and Scheduling* as well as *Conference Management* (*CM*) are employed to deal with these losses since they all try to improve the workflow and reliability of project planning.

LPS is a control system designed to improve project planning reliability by minimizing the gap between planned and executed schedule tasks [45,46] thereby identifying, analyzing and improving project inefficiencies. *LBMS* as a location-based planning and controlling system enables better workflows for crews of construction projects thus increasing productivity and minimizing interruptions [47].

Work Structuring and Scheduling enables project managers to align project's processes such as engineering, design, supply chain, resource allocation and on-site assembly in order to make workflow more reliable and responsive [48,49]. This allows for more efficient processes across all interfaces thus improving overall project performance and coordination and reducing idle times [50]. Garcia-Lopez et al. (2019) have tested the Activity and Flow-based Work Structuring Method (AFWSM), a *Work Structuring and Scheduling* method on three different construction sites. Through activity and flow-based schedules, project managers were able to further improve communication between project stakeholders and the understanding of the interfaces between the different activity types and flows [48].

Conference Management (*CM*) ensures that most of the common topics during a project meeting, like questions related to schedule, costs, quality and safety are analyzed and discussed among project team members and properly addressed for the coming period [38].

Similarly as these Lean methods attempt to improve work flow as well as planning and controlling of ETO projects by providing up-to-date schedules, Industry 4.0 technologies support ETO processes by enabling decentralized decisions based on real-time data acquisition and communication [51].

Exemplary Industry 4.0 tools to deal with project management inefficiencies are *Web Portals*, *Real-Time SCM*, various forms of *Cloud Computing* and *BIM* since they support and enhance the existing Lean methods by mainly providing the means of communicating and exchanging real-time data amongst all project stakeholders.

Web Portals allow for the integration of suppliers, manufacturers and distributers allowing to improve information sharing as well as communication [52,53]. *Cloud Computing* is a collaboration technology that uses the internet to share data from numerous sources and reduces flawed and delayed decisions due to out-of-date and incorrect information [36,54,55]. *BIM* in turn helps to monitor the project progress as well as the construction supply chain by collecting and analyzing real-time data coming from different actors of the project, such as contractors, suppliers and site personnel [56].

3.5. Losses caused by the Fabrication department

Losses caused by the Fabrication department involve all types of wastes that are caused during the production phase but only encountered within the assembly on-site. As practical examples, incomplete deliveries of material or components to be assembled as well as errors made during the Fabrication phase like wrong drilling of holes can be mentioned.

Just-In-Time (*JIT*), *Standardized Work* and *Poka-Yoke* are proven Lean methods in eliminating uncertainties and constraints, such as overproduction, defective products, waiting times and incomplete deliveries [57].

Poka-Yoke or error-proofing is used to check ahead of errors in the production or assembly process [58]. *JIT* ensures that the correct quantities of the right material are delivered to the exact location when needed [59]. This helps to avoid overproduction or a lack of material on-site [38].

Accurate and timely information sharing is an imperative for successfully implementing *JIT* [60,61] Industry 4.0 practices support this by providing actual and real-time data. These tools include *Management Information System (MIS)*, *Augmented Reality (AR)* and *Virtual Reality (VR)*, *RFID* and *Autonomous Robots*. *MIS* integrates various communication technologies and provides an effective exchange of information across all different parties [62]. *AR* and *VR* aid in product and process visualization. *VR* can be used to simulate real-life production lines to find manufacturing problems and bottlenecks to be tested virtually with the aim to find an appropriate solution [63]. In *AR,* the simulation is overlaid to the real-world view. Real-time manufacturing data collected during production processes combined with *AR* enables intuitive and effective interaction between the user and the smart machine reducing manufacturing errors [64]. *Autonomous Robots* in Industry 4.0 context can interact with one another and work safely side by side with humans [65]. They are the prerequisite for autonomous production which can complete tasks more safely, flexible and versatile and thereby reducing manufacturing errors and production time [65]. *RFID* supports the wireless information and communication between material and production thereby helping to continuously monitor the status and location of material batches [5]. Through structured expert surveys of over 100 US manufacturing managers, Zelbst et al (2014) could show that the use of *RFID* technology and subsequent information sharing enhances a manufacturer's *JIT* leading to improved operational performance. *RFID* incorporated into an established ERP system allows manufacturers to become more efficient by eliminating wastes during the manufacturing's logistics processes as well as offer better product quality and delivery response [61].

3.6. Losses caused directly by the Assembly On-Site

Losses caused directly by the Assembly On-site consist of all types of wastes that are caused directly by assembly works. As practical examples, a lack of tools on-site, the searching of materials or tools due to a bad order, failure of material handling systems, installation errors on-site, training of new crews and injuries due to safety breaches can be mentioned.

Common Lean methods for these type of inefficiencies are *Gemba Walk*, *Benchmarking*, *Total Productive Maintenance* (*TPM*), *Kanban*, *First Run Study*, *Six Sigma*, *Kaizen*, *Standardization*, *Prefabrication and Modularization*, *Just-In-Time* (*JIT*), *Daily Huddle Meeting*, *Total Quality Management* (*TQM*), *5s*, *Visualization Management* (*VM*), *Plan Of Conditions and Work Environment* (*PCMAT*), as well as *Poka-Yoke-On-Site*.

Gemba Walk is used on-site to investigate the source of an issue and to fix it [66]. *Benchmarking* can be used as a motivational tool by creating competition among work teams [67] and thus reducing installation time and errors. *TPM* is used for maintaining site operator's equipment preventing unnecessary tool down time [68]. *Kanban* can be applied on-site as an inventory control tool to prevent tools and material from running out of stock [69]. *5s* on-site is used to achieve proper construction site management through the *5s* – sorting, straightening, shining, standardizing and sustaining [38]. To teach new crews assembly on-site operations, *First Run Study* is useful since it requires investigation of errors and alternative approaches in order to lessen or preventing them [39]. Performance measurement or analysis of variations can be achieved via *Six Sigma* [70]. *Kaizen*, *TQM* or *Continuous Improvement Process (CIP)* can help to achieve a continuous improvement of the assembly processes by recognizing problems and developing new solutions [71,72]. *Visualization* or *Visual Management* is simply a tool to pass on specific instructions to workers on-site [38]. *Standardization* consists of a clean, organized and logical jobsite that leads to increased productivity [73]. *Daily Huddle Meetings* ensure rapid responses to current issues through involvement of all construction personnel [8]. A high degree of *Prefabrication and Modularization* can reduce construction time, reduce the frequency of errors during execution, improve on-site logistics and enable *JIT* deliveries [28]. *JIT* deliveries decrease the need for storage space on site, ensure availability of necessary materials when needed and reduce waiting time during installation [69]. In Andersen et al. (2012) the construction site of a hospital extension project in Norway was supported by implementing various Lean construction methods. All storage of material on-site was banned and moved to an off-site storage area. In this intermediate stock of purchased materials, the withdrawals were controlled by *Kanban*. Further, parts of material deliveries have been switched to *JIT* due to the use of an *e-purchasing* system [67]. *PCMAT* is applied to identify and mitigate possible risks by planning and controlling the entire safety of the workers [74].

Several Industry 4.0 practices could further aid in alleviating on-site inefficiencies. These include *Cloud Computing*, *Geographical Information Systems (GIS)*, *RFID*, *BIM,* and *AR* as well as *VR*.

Cloud Computing handles location data locally at assembly and construction sites and enables affordable and convenient data sharing and collaboration among all involved project actors [75]. Consequently, data can be shared allowing a real-time monitoring of progress and immediate response in the event of errors or delays [76]. *BIM* provides valuable information for assembly and construction progress monitoring and for assembly resources tracking, thereby notably improving the efficiency in communication between management team and on-site crew [75]. *RFID* is a technology that provides real-time information about the whereabouts of a product or material [77] making material flow visible throughout the entire supply chain. On-site it is used to track material, leading to less missing or misplaced material as well as less laborious material handling tasks [78].

GIS can be used in detecting conflict in material layout and evaluating the accessibility degree rate on-site [79]. *GIS* can be linked with *BIM* to plan the site layout and therefore improve the visual monitoring of assembly or construction supply chain management [80]. This can be applied to simulate the complete material handling on-site [81] which saves time in finding and handling material [82].

VR and *AR* provide digital data to physical parts thus bridging the gap between physical surrounding and the digital environment [83]. *VR* is used for simulating and interacting with a 3D model to facilitate training, understanding of complex tasks and projects [84]. *AR* can be applied for assembly tasks either in training, on-site guiding workers step-by-step through complex, manual tasks, supervisory control or even as a support for maintenance processes [83]. This improves performance and automation on-site and helps to make better decisions [85,86].

4. Limitation and implications for further research

The limitations of this paper are that the results are based just on scientific literature and only include works in English language. Practical works have not been considered. Further, we have not studied the barriers as well as difficulties to implement Lean methods or Industry 4.0 concepts and technologies in an ETO environment. The original purpose of the presented Industry 4.0 concepts and technologies have not been studied as well.

Therefore, we recommend researching the implementation barriers and difficulties of the presented Lean methods as well as Industry 4.0 concepts and technologies prior to their empirical validation in case studies.

5. Conclusion

The paper analyses traditional loss categories in ETO companies with subsequent assembly on-site and classifies them accordingly. A literature review was conducted to determine which Lean methods as well as Industry 4.0 concepts and technologies could be applied to mitigate these losses. Based on this, a framework was proposed that maps these Lean methods and Industry 4.0 concepts and technologies with the loss categories.

The results of this paper can help ETO companies to establish an assessment tool for implementing Lean and Industry 4.0 methods to lessen traditional losses and improve productivity. The article should be a first step for future studies and research validating the proposed framework with empirical data.

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