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Evaluation of Lean Manufacturing Tools and Digital Technologies Effectiveness for Increasing Labour Productivity in Construction

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Abstract: Multiple studies are devoted to problems of construction labour productivity and methods of increasing it. These studies contain systematized factors and the main measures that can be applied to influence them. However, the issues of reducingdowntime in design and construction by integrating Lean manufacturing tools and innovative digital technologies to increase construction labour productivity have not yet been actively studied. This paper examines the quantitative assessment of the impact of tools for Lean construction and the digitalization of business processes on labour productivity when implementing investment projects in development and changes in the effectiveness of projects. The conducted study contains an extensive review of the literature, identifies time losses as an important labour productivity factor, proposes a practical approach to the implementation of Lean 4.0 technology in the activities of a development company, and provides practical calculations of labour productivity for the existing project. Expert and calculated evidence of the positive impact of Lean 4.0 on labour productivity and performance parameters of construction projects are presented here. The effects of the introduction of tools and principles of Lean-digital technologies for construction project participants, as well as recommendations for the implementation of the proposed approach in construction practice, are discussed.

Keywords: construction; labour productivity; Lean construction; digitalization; efficiency; investment project

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1. Introduction

Today, there is a crisis of low labour productivity in the economy, known in the literature as the productivity puzzle [1,2]. At the present time, construction is facing this acute problem [3–5].

According to modern research, the construction industry is one of the largest in the world economy, and its turnover in 2023 is expected to exceed $10 trillion [4,5]. However, the productivity of construction has practically not changed, and has slightly decreased in the last 30 years [2,6–8]. Reducing unproductive time, which is a key factor affecting the current level of construction labour productivity (CLP), is an important scientific challenge for scientists and practitioners in order to increase construction productivity [9–11]. Reference [12] shows that a 10% increase in labour productivity leads to an almost two-fold increase in the profit of a construction company before taxation. This can inspire firms to increase construction labour productivity, especially by reducing downtime.

Factors that depend on the contractor include characteristics of the type and methods of the work organization and performance, as well as the motivation and qualification of the employees [13]. Most researchers [14–16] believe that improving the management of construction operations by using modern technologies and methods of work organization can be the key to increasing labour productivity. However, today, most construction project managers, construction customers, and contractors are focused mainly on technological progress and innovation, and to a lesser extent they are focused on industrial engineering and the labour productivity of their subcontractors and workers [4]. To increase productivity, the field of construction needs to improve its approach to work planning and execution, [4] which can be done by applying Lean construction and eliminating downtime. The use of Lean construction tools in development allows for improving production processes and reducing material waste and downtime, and thus improving labour resources [17,18].

A bibliometric analysis of related publications [3] emphasizes the importance of integrating the principles of Lean construction and innovative digital technologies to boost workflow efficiency and increase construction labour productivity. However, little attention is paid to this area in modern research.

LeanThe purpose of this study is to develop a practical approach to increasing labor productivity in construction through the introduction of Lean manufacturing tools and digital technologies, and to evaluate its effectiveness for an investment project.

This study develops a practical and scalable approach to reducing downtime in implementing investment projects (at the design and construction stages) by development companies through the combined application of the concepts of Lean construction and the digitalization of business processes. An assessment of the impact of increased labour productivity when implementing an investment project on the project's quality, timing, and cost, as well as on the NPV, is included herein. The proposed approach allows for taking into account the specifics of each project, so it can be applied both in housing construction and in other types of construction as well. The approach was applied to the implementation of a housing investment project, and its effectiveness was calculated without using the proposed approach and when determining the actual efficiency and productivity in the implementation of Lean 4.0 technology.

The structure of the article is as follows. Section 1 contains an overview of the main modern areas of research on construction labour productivity, factors and measures to increase it, and the definition of the purpose of this study. Section 2 provides a detailed review of the literature on problems, factors, and methods of increasing construction labour productivity. Section 3 provides methodological foundations for the introduction of Lean construction into the practice of implementing investment projects. A new approach to improving labour productivity based on the implementation of Lean 4.0 technology is given in Section 3. The results of the evaluation of the effect of the implementation of the proposed approach on the example of a real construction project are given in Section 4. The prospects and limitations for the wider application of the results of this research and its further development are presented in Sections 5 and 6. The logic of this study is presented in the figure below (Figure 1).

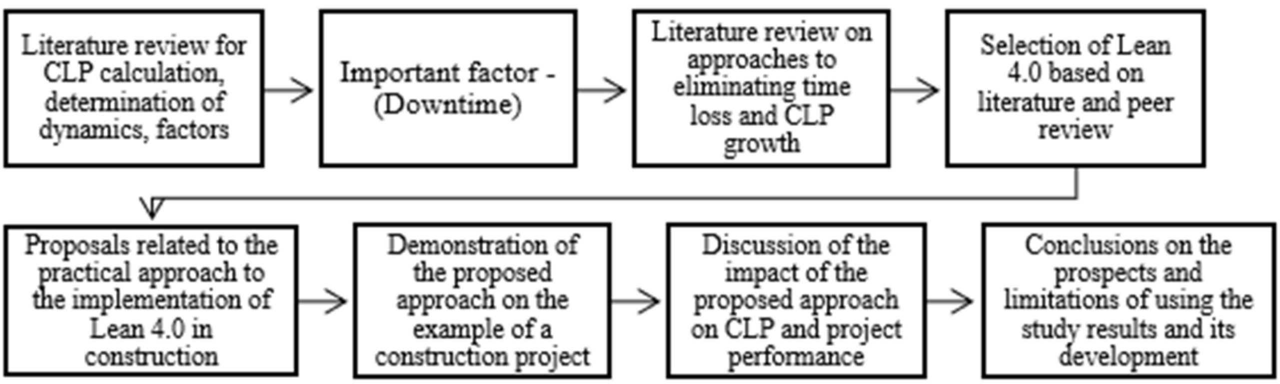

Figure 1. Research logic.

At the first stage, a review of the literature is carried out to determine the current state and dynamics of construction labour productivity, as well as factors, directions, and approaches to increase it. Particular attention is paid to research on the use of Lean construction tools and digital technologies to increase productivity in construction.

2. Literature Review

A detailed bibliometric analysis of research on monitoring labour productivity made in [3] indicates an almost exponential increase in the number of publications for the period from 2011 to 2022. With regard to the problems of our study, we will conduct a review of the literature paying special attention to the impact of downtime on CLP and approaches to reduce downtime.

2.1. Time and Measurement of Construction Labour Productivity

Labour is a resource that processes materials and directly creates construction products [19]. The focus of researchers on labour as the most important resource allows for a more objective and accurate measurement of productivity [16]. The labour productivity shows the quantity of products produced per unit of labour input [20]. Researchers define labour productivity in different ways, including as the quotient from the division of the volume of construction products into the labour costs [16,21,22], the productivity per hour of working time [23], and the time spent on performing a technological operation or manufacturing products [24]. The latter parameter is interpreted by many researchers as an output for the total amount of working time [23]. However, a number of researchers define labour productivity as the ratio of the volume of construction products and labour costs [25].

For the purposes of our study, the consideration of previous articles on measuring labour productivity at the micro level, as well as on the perception of labour productivity from the standpoint of labour and time costs, is important.

2.2. Construction Labour Productivity and Its Impact on the Efficiency of Projects

The direct impact of construction labour productivity on the profit of construction organizations is evidenced by the results of a number of studies [12,26]. Some of them are devoted to the assessment of construction productivity and its decline in comparison with other industries [6–8], the impact and importance of construction productivity both for the production of construction products and for the economy as a whole [5,9,10,27], and the impact of changes in labour productivity on the productivity of work in the construction industry [9].

At the construction site, workers are the main labour force in construction, and their productivity and quality of work have a significant impact on the implementation of the project and its key characteristics of quality, time, and cost [28–30]. In many countries, labour costs in the implementation of investment projects account for 30–50% of the total cost of construction, respectively, and labour productivity has a key impact on the profitability of investment projects [28,31,32]. Accordingly, increasing labour productivity can increase the efficiency of the project and provide cost savings for contracting construction organizations [29,33].

According to the results of reference [14], an increase in construction labour productivity by 10% in the UK will save £1.5 billion, which indicates the need to find effective measures to increase construction labour productivity.

Reference [34] indicates the presence of regional differentiation and differences in construction performance parameters. Reference [2] indicates the presence of two different groups in construction according to the performance criterion. The first group consists of large companies usually working in industrial and civil engineering, as well as large-scale housing construction, for which labour productivity is higher by 20–40%. The second group includes a large number of, as a rule, small companies specializing in certain types of construction, for example electrical or plumbing works and implement smaller projects, for example repair and construction works. The labour productivity in this group is lower than in the first one. The second group of companies cannot use breakthrough technologies (digital twins, BIM, exoskeletons, etc.) due to their high cost, but can implement Lean methods and elements of digitalization (an electronic document management system or an automated progress schedule).

The ability to calculate the impact of Lean technology and digitalization on labor productivity and project efficiency could encourage firms to implement them. However, such calculation methods are not well-studied in the literature [2].

The identification of factors affecting the level of construction labour productivity allows contractors to solve the problem by reducing unproductive time and cost overruns and increasing the efficiency of investment projects and their activities [35–37].

2.3. Factors Affecting Construction Labour Productivity

Most researchers agree on the influence of management factors, technologies, and labour force on the level of construction labour productivity and appropriate measures to increase it [22,38].

Factors related to the workforce have a direct impact on labour productivity. Reference [3] notes a number of articles dedicated to the identification of factors related to the workforce and work process improvement.

Modern studies consider the factors of information exchange and interaction between construction participants in investment projects as affecting labour productivity in the industry [39], and, given the number of construction participants, they are seen as decisive ones. Also, references [40,41] emphasize the importance and high degree of impact of the interrelated problem of requests for changes in the project (RFI) on construction labour productivity, since it is requests for changes that result in a large number of delays in the construction process, a corresponding increase in the cost of correcting changes in the project, and a decrease in labour productivity, which ultimately affects the success of the entire project. The aforementioned literature review [3] emphasizes the insufficient attention paid to the importance of project management methods, including Lean manufacturing and communication management in reducing the negative impact of requests for changes on labour productivity, and indicates the need for more thorough research.

Researchers are also focused now on the problem of information exchange and interaction between construction participants and its elimination, as well as the introduction of digital technologies, including BIM [42–45], which is recognized as a method of information exchange improvement for construction projects in most works.

The literature review highlights the factors affecting construction labour productivity that were mentioned by the majority of researchers. Researchers identify non-technological factors: related to the workforce (motivation and organization of work); factors of construction operations management (time loss and the introduction of Lean construction tools and other promising elements of construction operations' organization); external weather, and regulatory and other uncontrollable factors; technological factors. We agree with the opinion of [3] about the importance of integrating safety methods in construction, as well as the principles of Lean construction and digital technologies to develop the efficiency of the workflow and increase labour productivity.

2.4. Approaches to Increasing Construction Labour Productivity

A number of studies propose the introduction of industrial construction [46–48], and modern innovative construction methods [49,50], and innovative technologies [51].

The use of wearable sensors and other IoT technologies in combination with machine learning technologies allows for monitoring occupational safety and working conditions at a facility, which also affects the factor of labour resources [52,53].

Innovative technologies also include the use of information modeling technology. The results of studies, on average, show that projects based on BIM technology not only reduced costs compared to their counterparts, but also increased productivity by about 2.9% [54]. It is also very important that the difference between the labour intensity in BIM and non-BIM projects is measured in man-hours, according to the study results. The labour intensity of projects using BIM was less by about 103.5 days and such projects required fewer employees during the design stage [54]. Similar conclusions were made in study [42].

One of the main proven concepts is Lean manufacturing, which has been used by manufacturing enterprises for many years as a tool to increase labour productivity and reduce waste [55]. The construction industry adapted the principle of Lean manufacturing in the development of Lean construction, the principles of which also aim to increase productivity and reduce unproductive costs [17,56].

The results of study [57] show the priority of improving processes and minimizing waste in Lean construction practices, which makes it possible to improve labour safety in construction and ensure the constant development of labour resources and construction projects, even during crisis situations.

Modern research dedicated to the development of Lean construction suggests the use of BIM to improve the communication of all participants in an investment project and the construction process to improve the quality of the project and reduce waste in the future to increase construction productivity [3,42,45]. More recent studies have attempted to quantify the impact of BIM on productivity. Thus, in [58], the influence of BIM on six main performance parameters of the construction industry was investigated. The result of the survey of specialists showed that the key performance parameters are the quality, timely execution of work, and labour productivity. Reference [59] shows the effectiveness of the use of BIM in industrial construction on the example of the Canadian construction industry. Productivity improvements ranged from 75% to 214% compared to object modeling without the use of BIM technology [59]. Also, the researchers [42,59] mention the reduction in problems with the coordination of work in the field, faster decision-making and signing of documents, and, in general, the improvement of communication between the participants in the investment project, the reduction in construction time and project cost, the reduction in requests for change in the project, and the improvement of safety both during construction and at the operational stage as effects of using digital technologies in Lean construction. All of the above, in general, leads to an increase in labour productivity when designing the construction of facilities.

The literature review also showed a practical lack of research dedicated to the methodology of implementing Lean 4.0 in development projects in order to increase labour productivity. Accordingly, the study of a practical approach to the application of Lean 4.0 in development projects to increase labour productivity, demonstration of the proposed approach on the example of a project, and calculation of the corresponding effects will be relevant.

3. Materials and Methods: Proposed Approach to the Implementation of Lean 4.0 and Assessment of Its Impact on Labor Productivity and Efficiency of Development Projects

3.1. Approach to the Implementation of Lean 4.0 in Development Projects

Project activities are one of the most effective tools for involving personnel in the implementation of a company's strategic goals and for implementing large-scale improvements [60].

A Lean manufacturing project is a set of interrelated activities carried out within an organization as part of production system development to achieve established tasks within a specified period of time that are unattainable during regular functional activities [61].

Tasks that are solved during the implementation of projects, systematized on the basis of [42,62–64], are presented in Appendix A.

As part of Lean manufacturing project implementation, a number of activities retrieved from the scientific literature [55–57,62–64] which are aimed at improving a particular process are carried out (Table 1).

Table 1. Activities to be carried out during Lean manufacturing project implementation.

Activities to Be Carried Out during Lean Manufacturing Project Implementation		
No.	**Construction Process**	**Office Business Process**
1	Determination of total and actual scopes of work	Defining business process boundaries with the process owner
2	Determination of the required pace of work based on the working schedule and the current state	Conducting interviews with business process participants
3	The Standardized Work and 1 × 1 Problem Solving tools are used to carry out the analysis	Building a simplified business process diagram using the Structured Flow Chart tool
4	Determination of the daily need for materials, resources and methods of their supply	Detailing the business process diagram and agreeing it with the owner
5	Determination of the daily need for the number of workers	Analysis of the business process diagram and identification of problems, losses
6	Division of the work site into work zones of the same labour intensity sufficient for the work of one team during the shift	Development of a business process improvement plan
7	Drawing up a daily work schedule	Implementing improvements using the Kaizen tool
8	Development and implementation of improvements using the Kaizen tool	Ensuring control over the implementation of measures taken
9	Ensuring control over the implementation of measures taken	Development of regulations for this business process
10	Development of a standard for this type of work	

It is necessary to follow a clear methodology of the proposed practical approach to ensure the successful implementation of continuous improvement culture creation, personnel development in the field of Lean manufacturing, and organization of communication in the activities of development companies. Figure 2 shows the resulting practical approach to the implementation of Lean 4.0 in the activities of a development company.

The whole implementation process includes a sequence of actions that provides the employees of the development company with an understanding of the steps necessary to implement the Lean 4.0 toolkit to increase labour productivity. The practical approach model is conditionally divided into three stages, as shown in Figure 2. These are the planning and organization stage, the implementation stage of the Lean 4.0 concept, and the improvement control stage. Each stage includes a number of separate tasks and steps that represent the procedure of the developed practical approach model. An explanation of each step is provided below.

The preparatory stage consists in the creation of a Lean Manufacturing Department within the company, the development of documentation packages for the activities of the department, the development of training materials, and the comparison of business goals and the goals of the Lean Manufacturing Department through the identification of problematic processes.

At the implementation stage, all of the documentation that was developed at the preparatory stage and the Lean manufacturing processes are implemented, projects are managed, digital lean tools are selected, employees are trained, and the Lean manufacturing concept is promoted.

At the stage of control and improvement, the activities and efficiency of the Lean Manufacturing Department are analyzed, problem processes are updated, the training course is improved, and a program for talent pool development is developed. This stage is necessary to achieve maximum efficiency from the implementation of Lean 4.0.

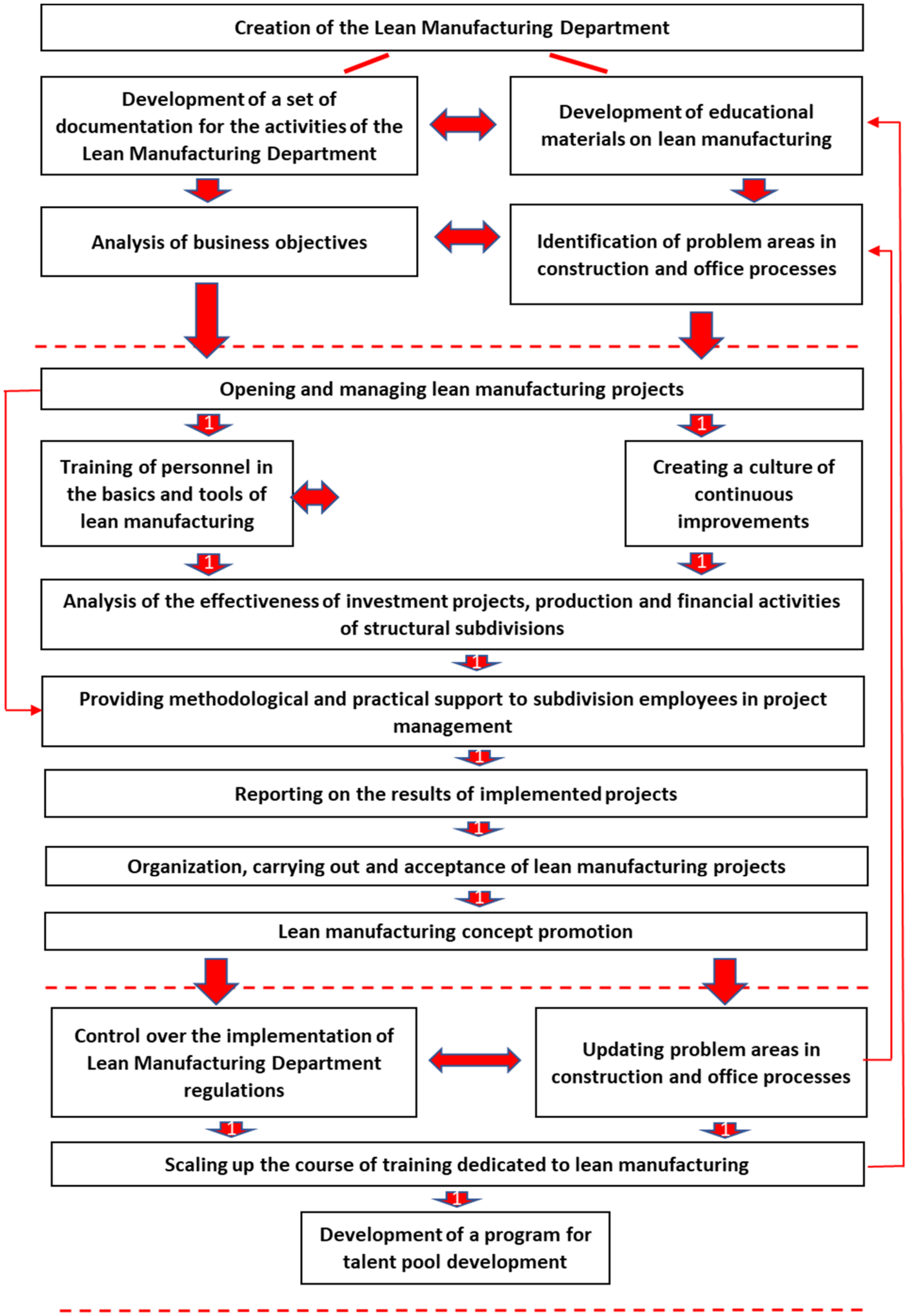

Figure 2. Practical approach to the implementation of Lean 4.0 in the activities of development companies.

The mechanism of implementing the Lean 4.0 project for the construction process is given in Appendix B, and for the office process—in Appendix C. Lean 4.0 projects for implementation in the company are evaluated and selected in accordance with Table 2.

Table 2. Overall project evaluation criteria.

No.	Criteria	Score	Weight	Offer Rating
1	Significance	1–5	20%	Score × Weight
2	Novelty	1–5	10%	Score × Weight
3	Efficiency	1–5	40%	Score × Weight
4	Scale	1–5	30%	Score × Weight
	Total score			Summarized score

The projects selected to justify the efficiency of Lean 4.0 implementation affect the time of commissioning of the facility when the main reason for its implementation was low labour productivity at the construction site and long office business processes, and these have high scores according to Table 2. Evaluation of the effects of the proposed approach to Lean 4.0 implementation is based on accounting for non-productive losses and is presented in Section 3.2.

3.2. Approach to Assessing the Effects of Lean 4.0 Implementation in Construction

The literature review presented in Section 2 provided insight into the main effects resulting from the reduction in downtime and the increase in productivity if Lean 4.0 is implemented.

The main effect is an increase in labour productivity, and the researchers also note a decrease in losses and costs, an improvement in the integration of participants in the process of work, and a corresponding decrease in both the number of comments on the project as well as collisions and requests for changes in the project. Reference [42] provides an expert and quantitative assessment of the effects. Moreover, the following approach to assessing the impact of Lean 4.0 on construction labour productivity is proposed as the continuation of this area of research. The starting point is downtime reduction, which in turn will lead to a reduction in labour costs and a reduction in time and money spent on correcting collisions, on RFI, and on comments, and will eliminate overtime work; further, the cost of materials is reduced both due to a decrease in costs due to an increase in labour productivity, and due to a decrease in losses. The cost of mechanisms is reduced, and the corresponding effects arise due to funds turnover acceleration, as well as a reduction in unforeseen and semi-fixed costs. In general, the reduction in man-hour overheads affects the reduction in the project implementation period, its quality improvement, and the reduction in its cost. The overall cost reduction leads to an increase in the project efficiency. The method of calculating the effects is presented in Table 3.

It should be borne in mind that the above approach is general, but each project has its own specific features and each Lean 4.0 event has its own characteristics regarding its effects. However, the list and sequence may be similar. Next, all the effects of the activities are summarized by project stage (design and construction), and the overall effect on the investment project is calculated.

Table 3. Sequence and calculation of effects from the implementation of Lean 4.0 to increase labour productivity.

Type and Sequence of Effect Formation	Formula for Calculating the Effect	Legend, Notes
Downtime reduction	$\Delta T = T_2 - T_1$	T_2, T_1—time spent on execution with and without Lean 4.0. It is determined by time measurement [18,34] or expertly based on duration of work before and after Lean 4.0 implementation [42]
Labour costs reduction	$\Delta T * C$	C—the cost of a unit of labour (payment per man-hour)
Reduced turnaround time	$\Delta D * Z$	ΔD—reduction of the period for performance (days, months, etc.) Z—costs per unit of time (day, month) For example, the cost of heating the site of the process operation, lighting, etc. can be considered as Z.
Reduction of material costs	$\Delta M * S$	ΔM—the amount of material savings, the amount of material losses prevented S—the cost of a unit of material [42]. It can be achieved through the formation of stocks for a longer period
Reducing the cost of machinery	$\frac{A + O}{30 * N}$	A—the cost of renting the mechanism per month; O—salary of the driver; N—the number of days by which the period of work performance has been reduced.
Reducing the cost of correcting comments, collisions, RFI	$\Delta R * Z_r + \Delta T * C$	ΔR—reduction in the number of comments, changes, collisions Zr—costs for correcting comments, changes, collisions
Reduction of semi-fixed costs	$(U_{sp} + U_a) * N$	U_{sp}—semi-fixed costs for the maintenance of the construction site; U_a—semi-permanent administrative and management expenses; N—the number of months by which the construction period has been reduced
Management costs reduction	$\frac{Z_g + Z_h}{365 * N}$	Z_g—costs for the general contractor; Z_h—costs for the customer; N—the number of days by which the period of work performance has been reduced
Increased turnover	ΔK	Volume of released working capital, including credit (acceleration of loan repayment, reduction of overpayment) [42]
Total costs reduction	$\mathrm{E} = \sum_{i=1}^{q} E_i$	q—the number of detected effects; E_i—the sum of the effect of the i-th type
Increased project efficiency	$\Delta NPV = NPV_2 - NPV_1$	NPV_2, NPV_1—NPV of the project with and without Lean 4.0.

4. Results

The methodological developments presented in paragraph 3 are considered on the example of residential complex construction.

During the implementation of the housing development project, the company faced a number of problems that, in one way or another, affected the commissioning period of the facility, and the main problem was low labour productivity at the construction site and long-lasting office business processes. The company's management decided to implement a number of Lean manufacturing projects in accordance with the practical approach which is presented in paragraph 3.1 in Figure 2.

In this paper, we provide a brief description and the results of Lean 4.0 projects implemented as part of using the proposed practical approach in the housing development project.

On-site design engineers collected data on labour costs, the cost of work, and the cost of unproductive downtime, and compiled tables for each of the projects. The tables below contain the results of each of the projects, the observed effects, and the initial estimate of the difference in the cost of time, labour, and materials, which makes up the total economic effect.

4.1. Project No. 1—"Enhancement of Masonry Works on the Example of a Housing Development Project"

The project is aimed at organizational improvement and the enhancement of masonry work to reduce the time needed for the work and eliminate losses. The project team consists of five people. The purpose of the project was to achieve a pace of work on cinder blocks laying of 7 days/floor. During the work on cinder blocks laying, the subcontractor was behind the schedule of work by 15 days, which entailed a shift in subsequent types of work. This problem occurred due to a lack of the required productivity. The reasons for the low productivity were the loss of time for transitions and the search for material, a large number of comments from the technical customer during the acceptance of structures, a long period for correcting comments, the workers not being united in squads, a lack of workplaces organization, the loss of time for cutting and laying cinder blocks, a lack of the required number of workers, and the low qualification of the workers.

During project implementation, the Standardized Work, 5S System, and Problem Solving 1 × 1 tools were used and seven Kaizen improvements were introduced. The project results are presented in Table 4.

Table 4. Results of Project No. 1.

	Before	**After**
Work progress rate	17 days/floor	6 days/floor
Number of comments from the technical customer	15	0
Productivity of works on laying cinder blocks	8 m^3/day	14.5 m^3/day
Period of delivery of floors to the technical customer	30 days	2 days
Work completion date	28 May 2022	10 May 2022

Project performance:

Reduced the deadline for the completion of works from 28 May 2022 to 1 April 2022 (58 days); at the same time, 1 day of delay in the delivery of housing to the customer costs 26,040 USD per facility (14 sections). The project was implemented for sections 9–12 (four sections).

4.2. Project No. 2—"Increasing the Efficiency of Installation of a Heating System on the Example of a Housing Development Project"

The project is aimed at increasing the efficiency of the installation of heating systems by identifying and eliminating losses and organizing the production line method of construction. The delay in the work schedule was due to a lack of the required productivity for the installation of the heating and heat supply system of the parking lot. The general contractor was meant to deliver the work on heating system installation in time to start finishing work on the parking lot in a timely manner in winter. The reasons for being behind were the lack of a system of continuous production of works, and losses due to expectations and transitions.

The project team carried out a number of activities to improve construction and installation works. The initial situation and the target state were analyzed and built using the Standardized Work tool. Workplaces were organized according to the 5S system, as shown in Table 5.

Table 5. Results of Project No. 2.

	Before	**After**
Pipeline installation productivity	85 l.m./shift	270 l.m./shift
Console manufacturing productivity	28 pcs/shift	70 pcs/shift
Pipe fabrication productivity	200 l.m./shift	270 l.m./shift
Existing stock of materials to ensure installation	2 days	21 days
Downtime of workers waiting for the material	1–3 days	0 sec
Number of comments made in the course of structures acceptance	8	2
Work continuous production system	No	Yes
Uninterrupted system for supplying blanks from the workshop to the installation level	No	Yes

By applying the project implementation methodology, the work execution period was reduced from 23 December 2022 to 15 October 2022 (68 days).

Project performance:

In the case of failure to implement the project, the statement of conformity would have been received 30 days later as compared to the planned date.

Heat supply should be provided at the parking lot to perform the following type of work (finishing). The duration of works on heating supply provision was reduced by 68 days. In the case of failure to implement the project, it would have been necessary to equip the premises with heat guns to maintain the required temperature in the parking lot.

4.3. Project No. 3—"Enhancement of Project Equipment during the Implementation of Project for the Provision of Mechanical and Electrical and Telecommunication and Warning Systems"

The project presupposes design solution adjustments to reduce the duration and cost of the project. The implemented improvements are presented in Table 6.

Table 6. Results of Project No. 3.

Before	**After**
Fire protection engineering equipment (Manufacturer A)	Fire protection engineering equipment (Manufacturer B)
Analogue—additional equipment is required to interface with the facility fire protection system	Addressable—direct interfacing with the facility fire protection system
Production time of the fire protection engineering equipment is 6–8 weeks	90% of fire protection engineering equipment is available in stock (10% of complex fire protection engineering equipment is manufactured in 4–6 weeks).
The fire protection engineering equipment of this manufacturer has not been used before and is not used at other facilities of the company	The fire protection engineering equipment of this manufacturer has already been used at other facilities of the company.
Different manufacturers produce automatic fire alarm system for the facilities	A single manufacturer produces the automatic fire alarm system for the facilities
The cost of fire protection engineering equipment and additional equipment —102, 955 rubles	The cost of the fire protection engineering equipment—49, 490 rubles (50–60% lower than the cost of fire protection engineering equipment offered by the manufacturer A)
Difficulties with technical support due to different manufacturers	A flexible technical support service.

During project implementation, 115 units of fire protection engineering equipment were replaced, the equipment delivery time was reduced, and the duration of installation was reduced from 74 to 21 days.

4.4. Project No. 4—"Optimization of Deadlines in Business Processes of Procurement Procedures through Digitalization"

The reasons for this problem was the low automation of processes at the electronic trading platform (a form of commercial proposal in electronic format created in Excel, which the participant was supposed to fill out and the employee of the Procurement Procedure Organization Directorate must check, so that there are no discrepancies or incorrect initial data (bid initiation request)). In the course of implementation, an electronic document management system (EDMS) was applied.

The results of business process digitalization are presented in Table 7.

Table 7. Results of Project No. 4.

Parameter	Before	After
Tender duration	48 working days	25 working days
Time of technical project documentation approval with minor changes	10 working days	4 working days
Time for the correction of errors in the tender initiation request	3 working days	1 working day
Time spent on the review of the offer by an employee of the Procurement Procedure Organization Directorate	3 h	1 h
Working documentation reference validity period	2 weeks	5 years
Time spent by an employee of the Procurement Procedure Organization Directorate to check the operability of the working documentation reference	0.5 working days	0 working days

The Lean 4.0 project affected four types of tender procedures, and the period of implementation of the investment project for the construction of the residential complex was reduced by 92 days.

4.5. Project No. 5—"Implementation of Online Checklists for Operational Quality Control and Organization of Reference Areas during Construction and Installation Works"

The project presupposes the organization of reference areas at the beginning of the work in order to identify comments and deviations early, as well as the development and implementation of an electronic online checklist for operational quality control aimed at reducing the time of transfer of structures to the technical customer and reducing the number of comments. The results of the project are summarized in Table 8.

Table 8. Results of Project No. 5.

Parameter	Before	After
Number of comments from the technical customer	12 pcs/section	0 pcs/section
The planned position of the structures corresponds to the design	No	Yes
The deviation of the wall surface from the vertical exceeds 10 mm	Yes	No
The thickness of horizontal and vertical joints exceeds permissible values	Yes	No
Period of structures delivery to the technical customer	30 days	3 days
Number of attempts to deliver the structures to the technical customer	6 times	1 time
Method of operational control	Visual	Check list
Saving the history and analytics of comments	No	Yes

As a result, the number of alterations was reduced by 654 m^2 of the brick wall.

4.6. Project No. 6—"Improved of Design Solutions for the Arrangement of the Pit Sheeting System"

The project is aimed to adjust design solutions for the arrangement of the pit sheeting system in order to reduce the cost of the project and the timing of the work.

The project results are presented in Table 9.

Table 9. Results of Project No. 6.

Before	After
The duration of work is 152 calendar days	The duration of work is 100 calendar days
Struts supported by a concrete insert in the foundation plate are included in the pit sheeting system	Struts supported by a concrete insert in the foundation plate are excluded from the pit sheeting system;
Installation of the sheeting system and earthworks are carried out in three stages—work zones;	Installation of the sheeting system and earthworks are carried out in a single work zone, without division into stages;
Benching is developed as a separate type of work;	Benching development is not a separate type of work;
The specific quantity of metal per sheeting system structure is 256,026 tons.	The specific quantity of metal per sheeting system structure is 115,098 tons.

Lean manufacturing project implementation made it possible to reduce the duration of work by 52 working days and reduce the specific quantity of metal per structure from 256,026 tons to 115,098 tons.

4.7. Project No. 7—"INTERACTION and Work with International Architectural Bureaus"

The project presupposes remote work based on EDMS with a foreign architectural bureau to reduce the time of project development and adaptation. During the analysis of the initial situation, the risk of failure to meet the design period of 423 calendar days was identified. Problems that affected design period extension were identified and described using the 4M matrix. During process analysis using the Standardized Work tool, a table of balanced work was created and the target design period was determined—310 calendar days. The results of the project are summarized in Table 10.

Table 10. Results of Project No. 7.

Parameter	Before	After
Conclusion of a contract with a foreign architectural bureau	30 calendar days	30 calendar days
Repeated conclusion of the contract in case of impossibility to implement the project	30 calendar days	0 calendar days
Suspension of the project for making a decision in connection with the start of the Special Military Operation	30 calendar days	30 calendar days
Concept design development	90 calendar days	113 calendar days
Confirmation of the possibility to transfer money to the foreign architectural bureau	47 calendar days	47 calendar days
Restriction of the Central Bank on advances to foreign companies	114 calendar days	114 calendar days
Additional adjustment of main design solutions due to increased requirements of Russian design standards	30 calendar days	0 calendar days
Suspension of the project due to sanctions imposed on currency transfer	64 calendar days	64 calendar days
Conversion of the model from foreign to Russian software	30 calendar days	0 calendar days
Architectural general concept adaptation by the General Designer	183 calendar days	0 calendar days
Additional meetings to clarify the boundaries and scope of responsibilities of the design participants	30 calendar days	0 calendar days
Schematic design development	120 calendar days	122 calendar days
Design supervision by the foreign architectural bureau	45 calendar days	45 calendar days

Applying the EDMS, the term of work with the foreign architectural bureau was reduced by 113 calendar days. Administrative expenses and the amount of interest that would be required to be paid to the bank for an additional 113 calendar days of design was determined to be 668,750 USD.

5. Discussion of the Results of Using the Proposed Approach

Lean 4.0 projects implemented according to the practical approach proposed in paragraph 2.2 of the investment project for the construction of a residential complex gave the following results in accordance with the assessment methodology presented in paragraph 3.2 hereof (Table 11).

Table 11. The total results of Lean 4.0 project implementation according to the practical approach proposed in the investment project for the construction of a residential complex.

Lean 4.0 Project According to the Practical Approach	Results		
	Duration	Quality	Cost
Project No. 1	-58 days	The number of comments reduced from 15 to 0	decreased by 431,562.5 USD
Project No. 2	-68 days	The number of comments reduced from 8 to 2	decreased by 647,187.5 USD
Project No. 3	-53 days	-	decreased by 49,270.8 USD
Project No. 4	-92 days	The number of contractor's comments reduced from 26 to 2	-
Project No. 5	-18 days	The number of comments reduced from 12 to 0	decreased by 14,687.5 USD
Project No. 6	-52 days	-	decreased by 118,750 USD
Project No. 7	-113 days	-	decreased by 668,750 USD
Total	-454 days	The number of comments reduced from 61 to 4	decreased by 1,930,208.3 USD

As can be seen from the table, the productivity increased by 37%, the quality improved by more than 15 times, and the cost of construction decreased by 1,930,208.3 USD. It should be noted that the increase in labour productivity is achieved by reducing the unproductive time and labour intensity (time for execution) of certain operations due to the digitalization and development of business processes when implementing Lean 4.0 projects.

There is also a decrease in the number of comments, partially due to an increase in the reliability and speed of obtaining information as a result of business process digitalization, which contributes to a decrease in requests for changes in the project (RFI), which is the most important factor in construction labour productivity according to the results of clause 3 hereof.

Also, it is necessary to take into account employee displacement in the effects of Lean 4.0 project implementation, as well as whether labour costs are reduced (Table 12).

Table 12. Calculation of the amount of savings from employee displacement while increasing labour productivity in the investment project for the construction of a residential complex due to the implementation of Lean 4.0 projects.

	Design Stage	Construction Stage
Reduction by days	113	341
Number of staff	20	300
Average salary per month	1875 USD	1250 USD
Average wages per day	84 USD	57 USD
Amount of savings	189,840 USD	5,831,100 USD

Using the tools, methods, and technologies of Lean manufacturing at all stages of the investment project, one can achieve significant reductions in both finances and the construction time due to the growth of labour productivity. To reduce construction time, Lean 4.0 can be applied to any residential facility.

Taking into account Lean 4.0 project No. 7 from paragraph 3 hereof, we present a comparative table (Table 13) of residential complex design stage implementation, taking into account the practical approach to the implementation of Lean 4.0.

Table 13. Comparative table of characteristics of the investment project of residential complex (design stage).

	Cost of Design	Design Duration
without taking into account the practical approach of Lean 4.0	3,939,166 USD	16.8 months
taking into account the practical approach of Lean 4.0	3,077,375 USD	13.1 months

Based on the determined cost of construction and duration of construction of the underground and above-ground parts of the building, as well as taking into account the Lean 4.0 projects No. 1, 3, 4, and 5 (for the above-ground part of the building) and projects No. 2 and 6 (for the underground part of the building) from paragraph 3 hereof, we present a comparative table (Table 14) of construction stage implementation applying Lean 4.0.

Table 14. Comparative table of characteristics of the investment project residential complex construction (construction stage).

	Cost of Construction	Construction Period
without taking into account the Lean manufacturing methodology	190,210,458 USD	51 months
taking into account the methodology of Lean manufacturing	183,046,812 USD	39.6 months

The introduction of Lean manufacturing made it possible to increase the productivity of work by more than 20%, and, as a result, reduce the time of investment project implementation. In addition, the practical approach under consideration has a positive impact on the cost of project implementation and allows for saving more than 5% of the planned financial resources.

Seven Lean manufacturing projects were implemented at the facility which have a positive impact on the project efficiency (Table 15).

Table 15. Performance indicators of the investment project for residential complex construction before and after Lean 4.0 implementation.

	NPV, USD	IRR, %	Payback Period (Downtime), Years	Payback Period (Discounted), Years
before implementation	78,132,968.7	26,587	7.3	8.8
after implementation	86,158,406.3	32,070	6.2	7.7

The calculations presented in this section correspond to the methods of calculating construction labour productivity adopted according to the literature [16,23,24]; reflect the impact of labour productivity on the implementation of investment projects in accordance with paragraph 3.2 hereof (the effects are calculated according to the following logic: labour productivity—reducing time—reducing costs—increasing project efficiency). The above-mentioned correlates with the results of [9–12,16,24,29,33]. The basis of the proposed practical approach is the combined application of business processes digitalization [42–44,54] and the concept of Lean manufacturing [3,17,42,45].

The results shown in this section are calculated for the construction company. However, the effect of Lean 4.0 implementation is received by project companies, project customers, and investors as well. Increased financial indicators of the project are important for the investor. The effects for design companies and construction customers must also be calculated and justified, which can be considered and accomplished in further studies.

6. Conclusions

In the course of this study, which includes an extensive literature review (including methods for determining construction labour productivity, its low level and unsatisfactory dynamics justification, and systematization of factors and identification of appropriate activities to increase labour productivity) and justification of methods for increasing construction labour productivity based on the introduction of Lean manufacturing and the digitalization of business processes and calculations for a specific project, a practical approach was proposed. It provides a certain procedure for introducing the concept of Lean construction along with digitalization (Lean 4.0) in a construction development company.

The main contribution of this study to science is to develop an adaptable and scalable approach to increase productivity in development companies for investment projects that will be based on the integrated implementation of Lean construction and appropriate digitalization tools [42]. The proposed approach to Lean 4.0 application in the company can be widely used in the design and construction of both residential construction projects and projects of other types of construction, applying and adapting various Lean 4.0 projects depending on the problems identified at the facility design and construction stages.

Evaluation of the results of the practical approach to the implementation of Lean 4.0 on a real investment project made it possible to obtain key information about its potential impact on labour productivity and construction efficiency. Particular attention is paid to the content and results of Lean construction and digitalization projects in applying the proposed approach to a real investment project, since they demonstrate the impact on the factors of labour productivity and its dynamics. When selecting digital tools, the methodology proposed in [42] for integrating Lean tools and digital technologies was used.

The study recommends that development companies implement the concept of Lean construction jointly with digital technologies in accordance with the proposed practical approach to increase labour productivity and the efficiency of ongoing investment projects. It can be concluded that there are a number of key effects: reducing labour costs, increasing labour productivity, employee displacement, reducing the duration of the investment project, improving the quality of construction (by reducing comments and changes in the project), reducing the cost of construction, and increasing the NPV of the investment project. The proposed approach also contributes to the creation of a database on the emergence of and ways to solve problems in business processes, as well as the possibility of the continuous training and motivation of employees, which fully corresponds to the need for continuous improvements in Lean construction.

Limitations of the study are as follows. Firstly, individual Lean projects for one investment project were implemented and evaluated, since it takes time (about two years) to implement a practical approach in general. Accordingly, in further studies, it is advisable to make an assessment for a longer time period, for all implemented projects of this development company. Secondly, the calculations did not take into account the full digitalization of the document flow of all participants in the investment project, which, according to [42], leads to an even greater increase in productivity. The use of BIM in the investment project was also not taken into account. In further studies, it is advisable to consider the cumulative effect of using Lean not only with the EDMS, but also with BIM. Also, the study does not provide a justification for staff incentives when using the practical approach. In the future, this should be taken into account to reduce the risks of resistance to change and increase staff motivation to increase productivity.

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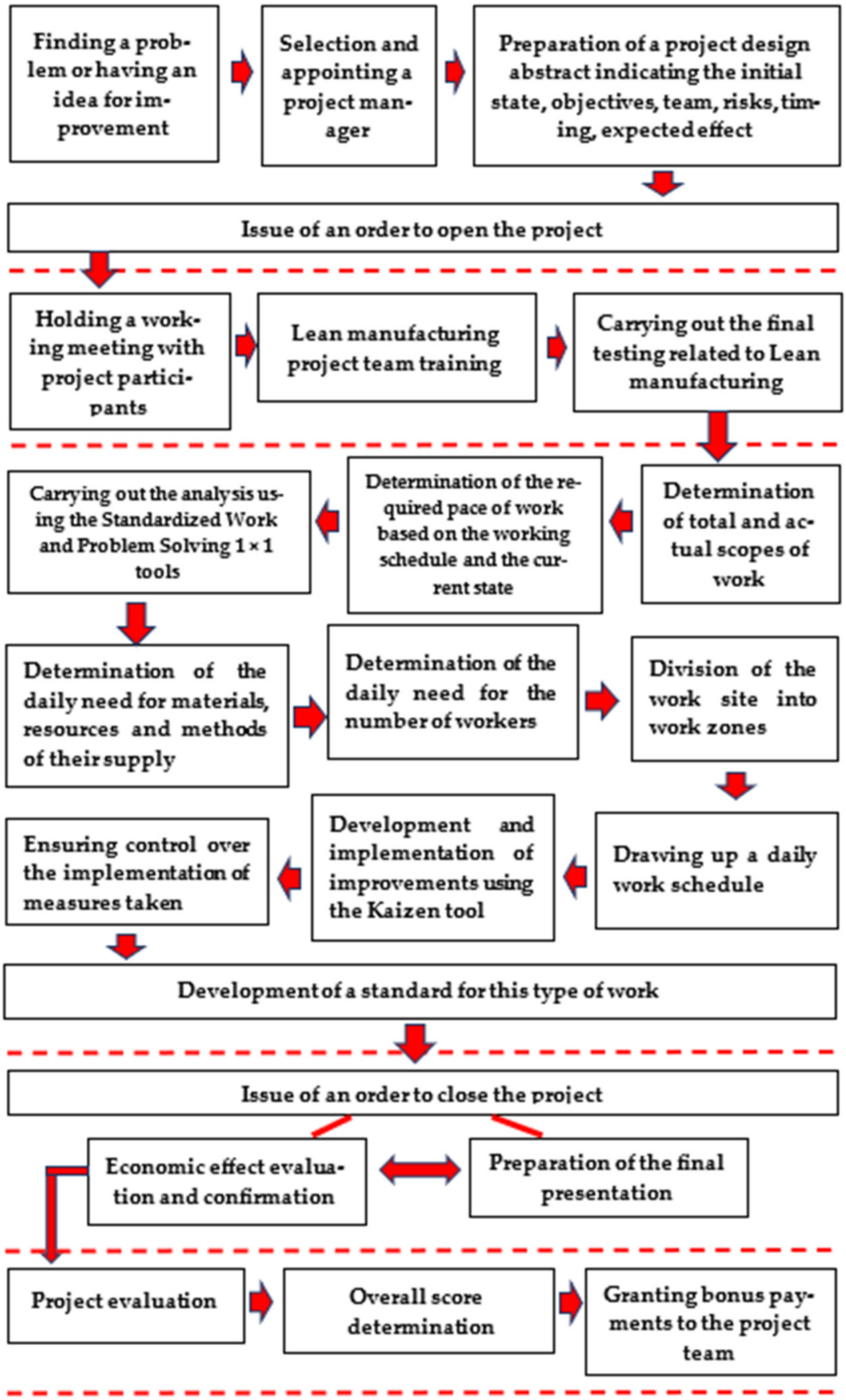
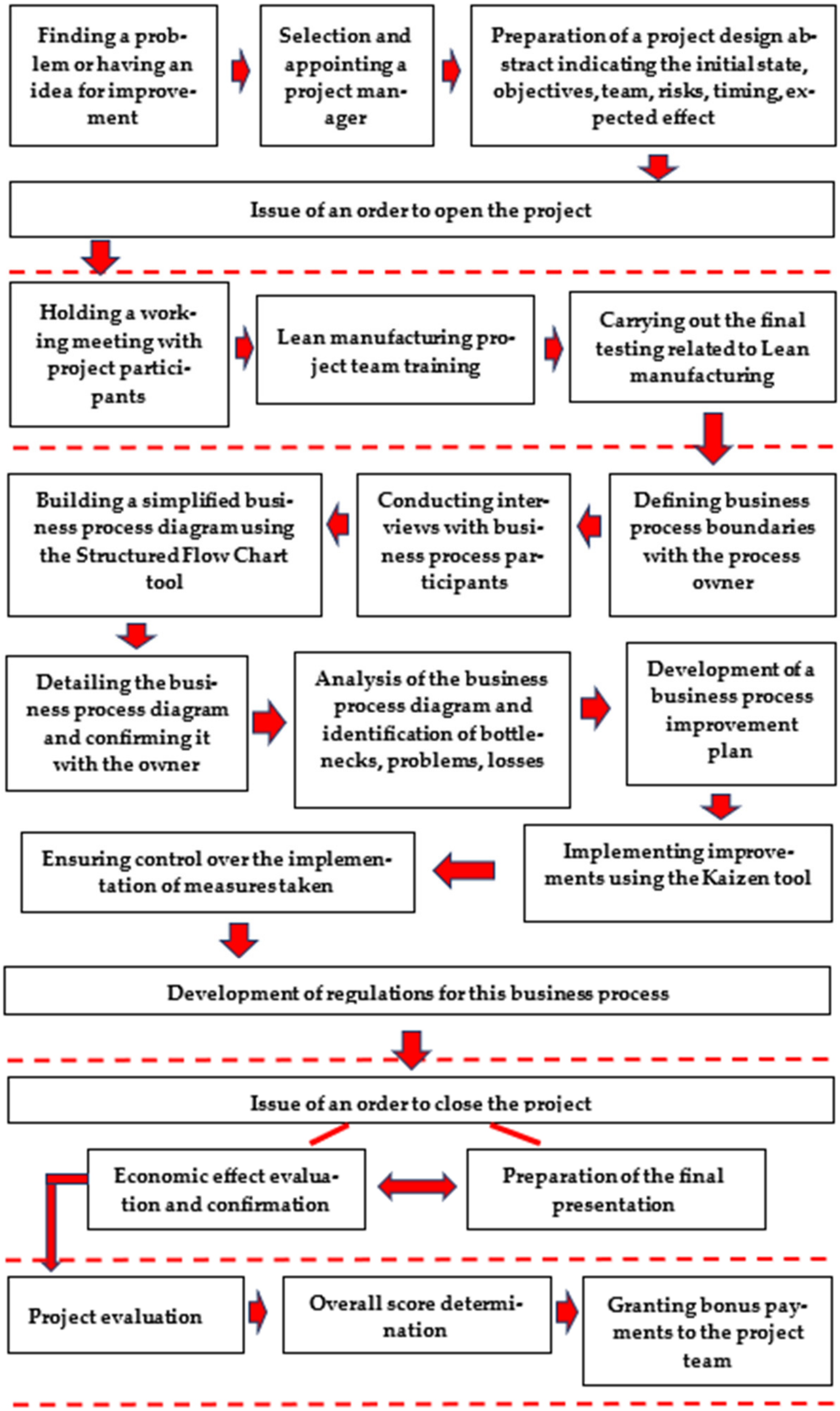
Appendix A. (Objectives of Lean Manufacturing Projects)

No.	Objectives of Lean Manufacturing Projects
1	Increasing the productivity of work performed
2	Improving the quality of structures/services provided/works performed
3	Improving business processes
4	Improving working conditions and safety, environmental standards
5	Risk reduction
6	Improving the safety of work execution/services provision
7	Improving the efficiency of the organization of workplaces, production sites
8	Reducing the cost of works/services/products
9	Reducing all types of production and non-production losses
10	Reducing labour intensity (optimizing the number, improving technology)
11	Changes in the organizational structure, reduction of unproductive costs
12	Eliminating duplication of functions
13	Saving material and energy resources
14	Reducing unscheduled/scheduled downtime of workers and equipment, improving the quality of equipment repair
15	Increasing the lifetime of equipment
16	Improving the turnover of in-process inventory, supplies
17	Applying new technologies introduced using Lean manufacturing approaches and tools
18	Identification of additional income (increase in profitability)
19	Development and marketing of new services/products

Appendix B. The Mechanism of Implementing the Lean 4.0 Project for the Construction Process



Appendix C. The Mechanism of Implementing the Lean 4.0 Project for the Office Process



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