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A Lean Approach for Real-Time Planning and Monitoring in Engineer-to-Order Construction Projects

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Received: 22 December 2017; Accepted: 7 March 2018; Published: 9 March 2018

Abstract: Engineer-to-order (ETO) construction companies are characterized by an off-site and on-site production. Often, budget deviations for installation works on-site are identified in a late stage when improvement actions cannot be applied anymore. Consequently, installation tasks are often affected by significant delays and/or reworks. This work proposes a "real-time" capable approach for planning and monitoring in construction and a corresponding information technology (IT) framework. The core is represented by the so-called "pitching" concept known from lean management, which breaks down large job orders into smaller controllable parts. It can be considered as the main enabler for gathering management information in real-time and to identify problems and their causes on time. The most noticeable consequence lies in smaller jobs and a software-aided punctual control that allows a better rescheduling capability and, thus reduced, delays. A case study is provided, showing how the model was applied and validated in an ETO façade supplier company.

Keywords: lean construction; process management; real-time progress measurement; information management; digitization; small and medium sized enterprises

1. Introduction

Make-to-order (MTO) production with a successive installation on-site is common in the plant building and construction industry. Considering Europe, and specifically Italy, in construction a high majority of companies are small- and medium-sized (SMEs), which makes the industry highly fragmented [1]. In many projects, most of the participating companies are composed of crafts with an artisanal structure. A special characteristic of this industry sector is that almost every project requires a new constellation of the involved participants. This leads to a high effort for coordinating the different companies. Moreover, the limited budgets and the inadequate use of methodologies led to a weak planning and measuring of the installation process. Moreover, components are produced in advance and have to be stored temporarily within the supply chain, causing high inventory levels and long delivery times (and, thus, inefficiency from a lean point of view). Sometimes, they are produced and delivered too late, causing inefficiencies on-site. In the worst case this can lead to construction interruptions (due to missing material), which can be considered as one of the main causes of construction cost explosions [2]. On the contrary, good planning and effective measuring of the construction progress are, notoriously, the preconditions to produce and deliver ETO components on time [3].

Traditionally, on-site problems are identified in a late stage, when intervention options become limited. Further, planning is centralized by the project manager, who plans the jobs based on the available historical data and subjective estimations. Rarely, he involves the companies responsible for execution. This results often in unreliable and inefficient schedules. More in detail, the processing of large job orders occurs, which is one of the main causes for long lead-times and high levels of work-in-progress (WIP) in ETO construction supply chains [4].

Traditionally, the management of the installation site depends on the individual competencies of the responsible task leaders (site-manager or foreman). This creates significant problems to a company, especially if such figures leave, causing a great loss of knowledge and experience. More in detail, scheduling of construction projects has been done by considering average historical data from similar projects, which is adjusted to specific project requirements (initial delays, learning effects, and the need for rework) by construction managers [5]. Since construction work is not performed in a controlled environment (on-site instead of a factory environment), a high variability of workflow has to be taken in consideration [6,7]. The construction industry is affected by a highly-unpredictable and dynamically-changing environment. Practical examples are bad weather conditions, like enhanced wind speed, rain, or excessive low temperatures, which hinder the smooth performance of work, like the pouring of concrete, façade welding, and so on. Moreover, if material is delivered by truck delays on-site could be caused by traffic problems, like accidents, jams, and so on. A high variability of workflow can often be caused by changing customer requirements, which means that components have to be replaced during execution inducing delays on-site. Furthermore, another specific challenge that the construction industry has to deal with is the necessity to set up, within every project, an effective collaboration between the participants [8].

Here, two different views have to be considered: (1) a "top-down" coordination among companies, (usually done by the general contractor) and (2) a "bottom-up" coordination within companies (e.g., between off-site fabrication and on-site installation). The two mentioned views are not synchronized sufficiently with each other. Thus, schedules cannot be followed on-site (e.g., insufficient resource availability).

A novel approach is required to:

- split complex jobs into smaller and more manageable elementary tasks;
- improve the planning and scheduling phase, both facilitating the correct resource and construction areas allocation and the consequent progress control;
- provide an information platform that enables real-time feedback processes, in order to increase the capability of timely and effective correction interventions.

Moreover, digitization would be helpful to connect the various actors involved in a plant building and construction project, de facto creating the opportunity of implementing a real-time event management system. In brief, when a job is stopped or delayed by a generic issue, actions to resolve the issue itself should be immediately taken and, at the same time, all the other actors should be punctually informed, in order to activate the required countermeasures and to avoid further delays.

Today, Industry 4.0 is a highly-discussed research topic in the manufacturing industry [9–11]. According to [12], the major features of Industry 4.0 are so called cyber-physical systems (CPS) (embedded computers and networks), connected by the Internet of Things (IoT) and operating in a real-time collaboration between systems and humans. The construction industry is in its beginnings to apply and implement technologies and concepts known from Industry 4.0.

One of the first approaches to the digitization in the construction industry consists of building information modeling (BIM), providing standards for the construction design process [13]. However, much less effort has been invested in developing information technology (IT) to support the execution process on-site and to connect it with the design phase [5,14]. Thus, the identified deficits are listed as follows:

- Traditional scheduling and control systems do not support a collaborative and interdisciplinary planning of the installation process by the responsible figures (companies). As a result, schedules are not reliable.

- Conventional systems are not able to represent the installation locations of a plant or building, needed to measure the execution progress in detail. Usually, the progress of a task is mostly estimated and not measured with up-to-date quantities. Moreover, the project progress is not measured at frequent intervals (not in real-time). As a result, delays are identified when a task is going to be completed, and intervention options become limited.
- The schedule updating process is not incorporated in a sophisticated way, which means that if changes or delays appear, they are propagated to following tasks by shifting starting dates into the future.

Based on these deficits and knowledge gaps the research objective in this work is to develop a lean based approach to plan and monitor ETO construction projects in real-time, in order to identify (budget) deviations and undertake the appropriate improvement actions. We describe the methodology and the supporting IT framework used to apply the approach in practice. Special emphasis is given to visualize the interaction process between the planner and the software. In conclusion, the practical application and the achieved results in an industrial case study of façade construction are presented.

2. State of the Art and Research Objective

This section summarizes the approaches and methodologies found in literature regarding the planning and monitoring of ETO construction projects. We start with traditional project management methods, as they have been used for many years and move through the application of lean methods towards modern real-time monitoring methods. Traditional project management methods used for scheduling of construction projects are MS Excel spreadsheets for work planning or MS Project schedules visualizing Gantt charts generated on a Critical Path Method (CPM) basis [15]. In Collyer et al. [16], researchers found that traditional project management methodologies have difficulties in dynamic environments due to three major types of changes: (1) project goals; (2) materials, resources tools, and techniques; and (3) relationships with other projects. Therefore, these traditional project management methods are generally not sufficient for the research objectives of this work.

After the success of lean management in manufacturing [17], lean principles were also introduced in the construction industry. Under the term 'lean construction' different lean methods were transferred and adapted from production to construction; other methods were developed specifically for the construction industry [18]. Typical lean methods transferred to the construction industry are universally valid concepts, like Just-in-Time (JIT) or Kanban [19]. One specific method for lean construction management is the last planner® system (LPS), which was developed to improve the coordination of different trades on-site [20]. The main contribution of the LPS is that time scheduling is done in collaboration with the trades and crews that will execute the work on-site. The LPS is structured hierarchically, composed of three levels of scheduling [21]:

1. the initial planning, which generates the project budget and the initial master schedule, modelling important project phases and milestones;
2. the look-ahead planning, which details the initial planning and identifies early-on potential constraints hindering an efficient execution; and
3. the commitment planning, which often consists of weekly or daily plans of the tasks to be performed on-site. It integrates a feedback loop from site, where, in weekly meetings, the so-called percent plan complete (PPC) value is measured. For those scheduled tasks, that were not performed, the Reasons for Non-Completion (RNC) are recorded to possibly avoid future occurrences of similar problems.

Since its appearance, LPS has been increasingly applied in the construction industry, with a main focus on improving the reliability of schedules considering the PPC, the commitment plan and the reporting on RNC [22–28]. Specifically, most of the LPS applications focus on improving the reliability of construction processes by successively removing constraints with the help of the PPC indicator and RNC. However, the PPC indicator alone does not give exhaustive information whether the project will be successful: the PPC measures just the number of completed tasks in relation to the planned ones, without considering the used amount of resources (e.g., men-hours) in completing the tasks in the construction locations. As a result, the PPC value alone gives not exhaustive information about the current construction progress and the deviation from the initial plan. The focus of the LPS is the coordination between companies and the achievement of reliable schedules, but it lacks in the synchronization of the supply chain and the detailed monitoring of the construction progress.

Recently, LPS has often been applied together with the so-called Takt-Time Planning approach [29,30] referred to as a work structuring method. Takt-Time Planning and LPS can be seen as complementary in different aspects, since Takt-Time Planning can essentially expand LPS's formal mechanism of commitment management with more standardized work batches and, thus, contribute to continuous flow [30]. Takt-Time Planning makes use of clocked scheduling with time-harmonized work sequences and accordingly-coordinated activities. To this end, construction projects are structured into so-called "Takt zones" by identifying repeatable and non-repeatable construction elements in advance of execution [31]. The rhythm of the construction progress or, in other words, its "heartbeat", is determined by the so-called "Takt time". In fact, the utilization is very common in almost identical work sequences with high recurrence rates [32]. However, it also seems to be an interesting approach for ETO construction projects since recent endeavors have been made to find repetition in non-repetitive construction works on the basis of work density in order to circumvent this shortcoming [33].

'Activity-based' scheduling methodologies consider the installation locations only marginally, making a detailed and real-time measurement of the construction progress difficult. To overcome this hurdle Kenley and Seppänen [34] developed the location-based management system (LBMS) method. The approach focuses mainly on the repetition of tasks in multiple locations and on a continuous workflow, without an intersection or interruption of crews on-site. However, there is no systematic synchronization of the scheduling with monitoring and therefore deviations on-site are not recognized early enough to implement improvement measures on time.

Seppänen et al. [35] present the opportunities, which can be reached through the combination of the LPS and the LBMS. According to the authors, the major improvement potential resides in progress tracking, forecasting and continuous improvement of the construction process. More in detail, the contribution of the LBMS is the "systematic collection of progress data, forecasting future production based on actual production and alarming of upcoming interference" [35]. Considering the LPS, it highlights constraints, which have to be removed to allow the performing of construction works according to schedule. Based on case study results, by combining both systems it was possible to identify more problems earlier than by implementing each system separately [35]. However, no consideration was given to problems caused by late or early material deliveries or, in other words, the alignment of the supply chain with the construction progress.

According to Serrador et al. [36], based on the increasingly need to improve the planning and monitoring process in the IT project environment, companies changed from the traditional front-end planning to agile project management, which consists of a planning and monitoring process with multiple iterations throughout the development phase. Iterative methodologies, like the 'rolling wave' [37], can be considered as predecessors to agile methods. In agile methods, the so called 'frozen period' of project schedules is handled in a flexible way to address critical project goals [36]. However, in the construction industry there is a less reported use of agile methodologies [36].

A method used mainly for monitoring of construction projects is the earned value analysis (EVA). It is an industry standard method to measure project performance and progress in an objective way. The core part of EVA is to establish a direct relationship between the percentage of work done and the budget for that account [34]. In EVA, the difference between budget cost of work performed (BCWP) and budget cost of work scheduled (BCWS) is called the schedule variance (SV) and it measures the performance of progress against a schedule. Usually, if the SV shows a negative value the responsible manager tries to increase as much as possible the BCWP by anticipating work. As a result, work sequences are changed, without taking into consideration the negative impact on the performance of downstream trades. Notoriously, EVA is highly reliant on a detailed measurement of the project progress to reliably predict project performance [38]. However, EVA is used more by management levels and not to measure daily-based assignments in terms of planning reliability of short term-schedules (operational level).

Arbulu [39] affirms that construction projects should be managed like airports, where the control tower coordinates the departure and arrival of airplanes using real-time information. In the air-transport industry changes in schedules are frequent but, differently from the construction industry, they are handled in an efficient way. Real-time approaches are of great importance in the emerging trend towards Industry 4.0. According to Industry 4.0, machines, products and people in the production system are to be networked and can exchange data in real-time via the IoT [12,40]. Currently we can identify a gap in knowledge and traditional scheduling and control systems in construction because they do not, or only insufficiently, support collaborative planning of involved companies at the installation site [5,14]. In most of the cases installation progress is only estimated and not measured with sophisticated methods or tools and not retrieved in real-time [4,8]. Such unsynchronized information flows generate delays and do not allow an adequate reaction for problem-solving [8,40]. However, apart from partial RFID implementations [41], there are currently no comprehensive systems for real-time monitoring on construction sites.

The main knowledge gaps identified in the review of existing planning and monitoring methods are the following: Traditional project management methods like CPM are not sufficient for operational planning and monitoring of ETO projects in construction. The described general lean methods (JIT, Kanban) mostly allow only partly optimizations. EVA is often used for management levels rather than for operational planning and monitoring. The specific lean construction methods (LPS, LBMS, Takt-Time Planning) show the most potential for our research objectives, but lack in the synchronization along the supply chain and in the ability for real-time monitoring. Real-time monitoring is a highly-discussed topic in Industry 4.0 but, currently, there are no comprehensive systems available.

As a result, our proposed approach for planning and monitoring of ETO construction projects is based on specific lean methods from construction industry (LPS, LBMS, Takt-Time Planning) combined with real-time monitoring in order to achieve an efficient fabrication and delivery of components triggered by the installation progress on the construction site. Summing up the results of the literature review, the following research question (RQ) arises:

RQ: "How is it possible to plan and monitor ETO construction projects, in order to identify budget deviations and undertake the appropriate improvement actions in real-time?"

3. Research Approach

Figure 1 shows the applied research approach. In a first analysis phase, two types of analysis were conducted. In this phase, primary as well as secondary research sources were used. By analyzing existing literature and research papers (1—secondary research based analysis) the research team created an overview of the state of the art in research. Interviews with different companies from the ETO sector were used to analyze the kind of methods used by common ETO companies and to identify or confirm the problems that arise in daily practice (2—primary research based analysis). The results from the analysis phase were then used for concept design (3) to develop the proposed approach in this paper [42]. The first phase in the concept design cycle is usually referred to requirement analyses [43] (3a—requirement analysis). Once the requirements have been defined, the conceptual development phase takes place. In order to evaluate the proposed approach (4—proof of concept) the research team conducted a long-term study together with a manufacturer of façade and accompanied the company in an expansion project of a city hospital in Italy. Based on the results from the proof of concept phase, the research team implemented an IT prototype in order to apply the approach in a systematical and sustainable manner at the case study company (5—Implementation/commercialization phase). Currently, the research team is working on a commercial version of the developed IT prototype.

In addition, the research approach foresees also the definition of future need for research (6—future research), like an application in case studies from other trades, in order to motivate also other scientists to further develop and improve the proposed approach.

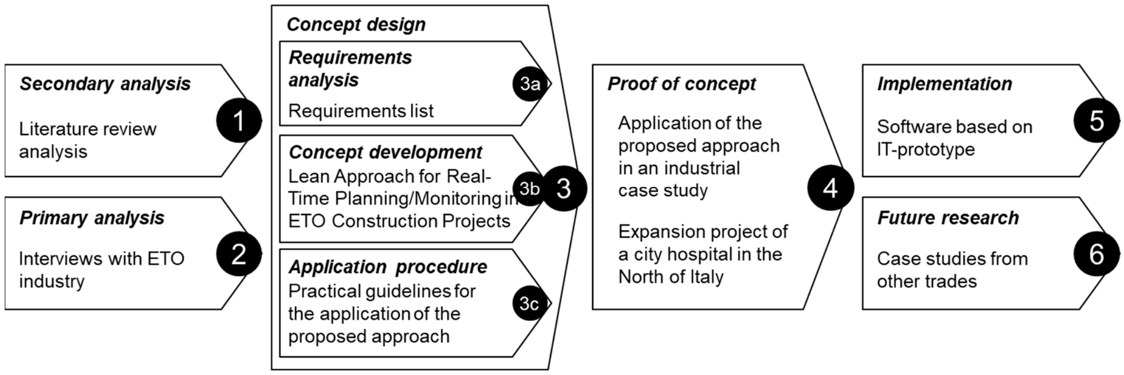

Figure 1. Phase model of the applied research approach.

4. Primary and Secondary Analysis

4.1. Secondary Analysis

In order to gain a better understanding of the topic, an extensive literature research and analysis was carried out at the beginning of the research. We conducted our keyword search using the Scopus database. In order to determine the conceptual boundaries of our research, we used the following keywords: 'construction supply chain' and 'construction supply chain management'. The search was limited to publications relating to the Scopus sub-area 'engineering", as conceptual boundaries. We considered conference contributions and journal articles. There was no restriction regarding time and language was limited to works written in 'English'. Using the above-described approach, we identified 70 publications. In order to select relevant studies, we screened every paper and decided whether or not the scope of the paper was relevant for our study on planning and monitoring in ETO projects. We identified so 46 papers with a focus on planning and monitoring in ETO projects. Table 1 shows the search approach and inclusion/exclusion criteria used.

Table 1. Inclusion and exclusion criteria of the literature review.

Limitation	Criteria	Count
Source	Scopus	—
Search terms and connections	ARTICLE TITLE, ABSRACT, KEYWORDS: "engineer to order" AND ("planning" OR "monitoring")	108
Sub area	LIMIT-TO "Engineering"	77
Time	No restriction	77
Source type	Conference proceedings, journal contribution	72
Language	English	70
Screening	Only papers with relevance for the study	46

Subsequently, a content analysis of the remaining papers was carried out in order to identify literature-based deficits of current approaches. Those results were used by the research team to define first literature-based hypothesis for improvement measures in a new approach for planning and monitoring of ETO projects. Table 2 shows the results of this literature analysis.

Table 2. Deficits and main requirements based on literature review.

Main Deficits	Derived Literature-Based Hypothesis	Main References
High inventory levels and long lead times	Reduction of waste and inefficiencies through lean management	[44–46]
Interruptions due to missing material	Synchronization of fabrication and installation	[44,47,48]
Problems identified in a late stage	Immediate or real-time feedback loops of schedule and budget deviations	[4,46,49]
Unreliable schedules and construction progress measurement		[4,47,49]
Centralized planning by project manager	Decentralized and operational monitoring and planning	[4,46,50]
Based on experience of persons rather than systems/methods	Systematic and methodological approach	[4,45,50,51]
Collaboration between participants	Collaborative planning and definition of installation tasks	[4,44,50]
Missing development of IT tools in construction	Digitization of planning and monitoring in ETO projects	[49,50,52]

4.2. Primary Analysis

The primary analysis includes interviews with companies from the ETO construction industry. The companies come from façade construction, steel construction and the building industry. In the course of the primary analysis, discussions were held in structured interviews with higher-level management positions, middle-level project managers and operational-level foremen. The interviews were structured in three parts:

First of all, the interviewees were asked about currently applied methods for planning and monitoring on the construction site. The interviews confirmed that mainly paper-based tools or simple IT tools (e.g., Microsoft Excel/Project) and only in a few cases enterprise resource planning (ERP) systems are used for the planning of construction processes. The feedback is not real-time, but mostly sporadic, unsystematic, and with long intervals.

In the second part of the interviews, respondents were asked about current deficits in planning and monitoring. In this part, too, the opinions of the interviewed persons coincided with the results of the literature analysis.

In the third part, the results of the literature analysis and the hypotheses were presented to the interviewees to discuss them in detail and receive practical input. In the opinion of practitioners, lean methods are still not used enough at the moment, although they are widely known. Particular emphasis must be placed on the introduction of a systematic approach and, above all, on systematizing feedback on the progress of construction work. Real-time is an important issue, but practitioners are aware that this requires the introduction of digital tools. According to the companies, decentralized feedback from foremen or workers is now technically possible (e.g., through the use of smartphones or tablets).

5. Concept Design of a Real-Time Planning and Monitoring Approach in ETO Construction

5.1. Requirements Analysis

Based on the primary analysis (interviews) and the secondary analysis (literature), a list with requirements for the concept for planning and monitoring of ETO construction projects was defined. Table 3 summarizes the results of this requirements analysis. Based on this list, the concept for the presented approach (see next sections) was finally developed by the research team. By taking into account the literature, on the one hand, and company interviews on the other, the authors tried to combine both theoretical approaches and practical experiences from the ETO industry.

Table 3. Requirements for planning and monitoring in ETO construction.

Requirements	Description
R1—Lean-based	Reduction of waste and thus consideration of lean aspects in construction supply chains.
R2—Process modelling	Standardized approach for process modelling of construction/installation tasks on-site.
R3—Synchronization	Synchronization of the planning at the installation site with production planning of fabrication.
R4—Systematic progress feedback	Systematic instead of casual or unstructured feedback of on-site installation progress.
R5—Quantitative construction progress measurement	Quantitative measurement of the construction progress instead of traditional estimations
R6—Decentralized feedback	Decentralized and thus more detailed monitoring of installation progress of tasks through foreman/worker instead of project manager.
R7—Real-time	Real-time feedback of installation progress to reduce delays and to increase responsiveness.
R8—Digitization	Digitization of planning and monitoring and thus substitution of paper-based approaches with digital and IT based tools.

5.2. Concept Development of the Proposed Approach

Usually, in construction, three major phases, design, planning, and execution, can be identified (Figure 2). In the design phase, architects and specialists work out the concept of the building and specify its technical content. Large job orders are passed from the design to the planning phase. Here, actors, like project managers or site supervisors, are engaged to perform the so-called organizational execution planning. Based on the design of the project, the logistics concept and the time scheduling are elaborated. Time scheduling is a critical part of the organizational execution planning. Traditionally, important information, like durations and the amount of resources needed, are taken from past projects or from estimates of the responsible planning actor (project manager). Moreover, a rough planning is done (e.g., activities are defined without considering the building locations or without taking into consideration the needed workforce), which makes it difficult to monitor the construction progress and to identify in advance problems causing budget overruns.

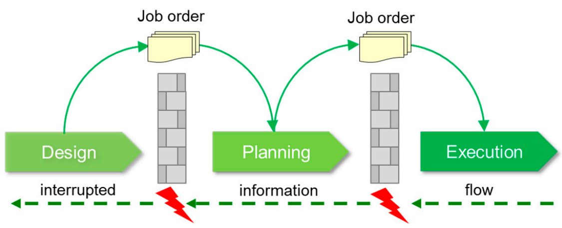

Figure 2. Traditional planning and construction.

On the contrary, in the proposed approach, the design, planning, and execution phases are interconnected. The collaboration of actors from design, planning, and execution is supported by an appropriate IT platform. The execution part encompasses actors working on and off-site and five categories may be identified. Considering the on-site workers, a grouping in three main categories, skeleton, envelope and interior construction is done. Considering the off-site ones, the first- and second-tier suppliers produce MTO components to be installed on-site. The proposed approach considers four main steps [53]: (1) process planning; (2) pitching; (3) synchronization; and (4) standardization—process templates, which are explained in detail in Section 5.3

The process planning step takes place at the end of the design phase. As visualized in Figure 3, actors from design, planning, and execution define in collaboration the construction process.

- Actors from design are responsible to explain the technological content of the building.

- Actors from planning are engaged to provide detailed information about the deadlines and the milestones of the project, as well as the logistics aspects (e.g., availability of material handling systems, places to store material).
- The foremen are responsible to provide information about the needed tasks (based on the technology content), their sequence, and the needed effort (e.g., workforce).

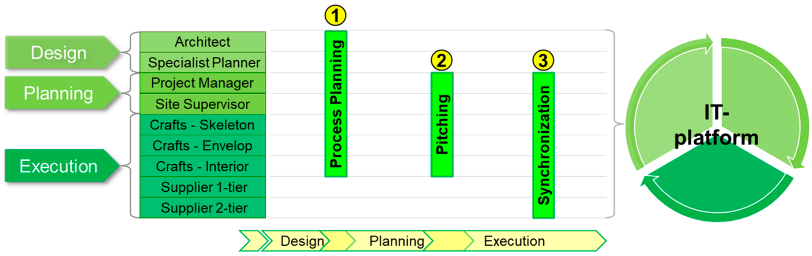

Figure 3. Collaborative planning and construction.

The pitching step is the core part of the approach. It is based on the concept of 'paced withdrawal' [54] in lean management, where a steady amount of work (production instruction) is given at the pacemaker process and, at the same time, an equal amount of work (in terms of finished products) is taken away. Rother and Shook [54] call this steady amount of production instruction "pitch" and in the manufacturing industry it usually ranges from 5 to 60 min.

By applying the 'pitching' approach to the construction industry, the customer demand (job order) is broken down in small lots with approximately equal size, allowing an optimal capacity saturation and minimal non-productive time. As a practical example, consider the activity 'façade installation' of a multistory building. Traditionally, the level of detail in the master schedule is structured as follows: (1) activities are set to a level of detail like 'installation of the substructure'; and (2) construction areas are usually set to levels (e.g., ground floor up to the fourth floor). As a result, this does not allow a measuring of the construction progress in real-time. Differently, according to the pitching approach from lean management, activities are subdivided in different tasks, like the activity 'installation of the substructure' is further split in 'installation of brackets', 'installation of basis profile', and 'security welding' were different crews can be directly assigned. Considering the construction locations, levels are further subdivided in construction areas (CAs) (e.g., the east façade of the fourth floor) and construction units (CUs) (e.g., the distance between two main axes of the building encompassing one CU). The difficult part is the definition of CUs in non-repetitive projects, where the job content differs significantly between the main axes of the building. Here, the construction progress cannot be measured by considering the completion of tasks in CUs in a specific time interval, but by introducing further measuring units (e.g., pieces, square meters, or running meters).

Figure 4 shows schematically the operating principle, where the execution part is subdivided in 12 equal "slices", within different job types (skeleton, envelop and interior). Every 'pitch' should be assigned a capacity flexibility. After every 'pitch', an appropriate quality control takes place and, if the work was not performed according to specifications, overtime has to be introduced. As a practical example, if the 'pitch' corresponding to a one week workload could not be completed, then working on Saturday should be introduced. According to expert interviews a capacity flexibility of ±20% should be considered. As a result, the following pitches are started when work is ready to be executed and an overall deviation is avoided/limited, thus avoiding the re-scheduling need.

The pitching approach is also applied to the supply chain, enabling a JIT or on-demand production and delivery of MTO components (Figure 5). Figure 5 shows the application of the pitching approach to a first-tier façade supplier company. As a practical example, consider task 1—installation of frames. Here, a lot size oriented prefabrication of components (e.g., the cutting of profiles), as well as an on-demand assembly and delivery to the site for installation is visualized (assemble-to-order

ATO). Usually, a pitch of 4 CUs with a crew composed of two workers can be reached on-site. If we assume that one CU requires one frame, this results in a required quantity of four frames per day or, in other words, 20 frames per week. As a result, if construction performance increases, more material should be requested from the supply chain and the production/delivery of MTO components should be increased. Otherwise, if construction performance decreases less material should be produced/delivered to the construction progress, avoiding an overfilling of intermediate buffer zones. The so-called one-pitch-flow (OPF) principle, know from lean management, can be easily applied, which means that the customer order flows in a continuous way from the supply chain to the installation site. Moreover, the pitch flows also on the installation site avoiding workflow interruptions. As a result, by releasing work in small batches (pitches), the parallelization is increased and the intermediate buffers throughout the supply chain and on the installation site are decreased. In conclusion, by applying the pitching approach, the following contributions to a successful project execution are obtained:

- Reduction of the overall supply chain and on-site lead time (time);
- Fast reaction to customer changes or identified errors (quality); and
- Enabling of on-demand delivery to the installation site, avoiding workflow interruptions due to missed material (cost).

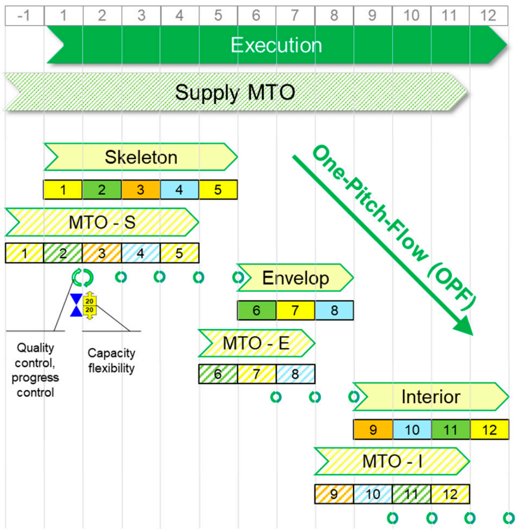

Figure 4. The One-Pitch-Flow approach for paced execution and supply.

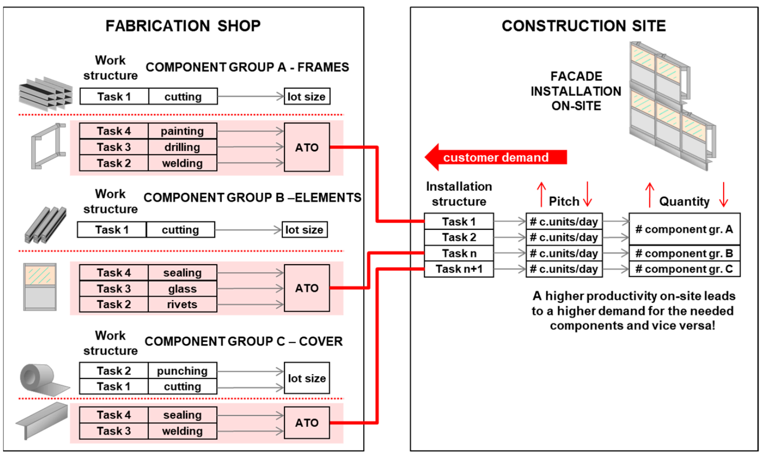

Figure 5. Pitching approach for on-demand production and supply (based on [55]).

5.3. Application Procedure

5.3.1. Process Planning

The main objective of process planning workshops is the collaborative planning of the execution process. According to Figure 3, actors from design, planning and execution define in collaboration the construction execution process. Here, the main entity consists of a task. It is defined as a working process on-site, which contains a defined job content and has to be performed in a specific CA. According to REFA [56], the job content is defined as the work type and amount in terms of hours and number of needed resources. The building structure is partitioned into physically controllable parts called CAs. An appropriate tasks sequence has to be negotiated by the participating actors, with the final aim to optimize the whole installation process. For every task in a specific CA, the needed 'pitches' are estimated by the participating actors responsible for execution [53].

5.3.2. Pitching

As illustrated in Figure 2, job orders are common in construction. As a result, large lot sizes are moved throughout the construction site and within the supply chain. Conversely, by means of the 'pitching' approach, job orders are divided into small controllable parts with the aim to monitor the construction progress in real-time (e.g., every day, every week). It is used to schedule and monitor repetitive as well as non-repetitive construction/installation processes. Figure 6 shows the formula and the detailed approach. "Pitch" is defined as a certain "job content" (e.g., days, weeks), which has to be completed by a specific 'crew' (consisting of a minimum number of workforce) in a limited 'construction area' (specific construction/building locations).

Figure 6 shows an example of façade construction, which is composed of three 'pitches'. Every 'pitch' encompasses a time frame of one calendar week (CW). Considering façade installation, four major tasks can be mentioned: installation of brackets (A), assembly of frames (B), glazing (C), sealing and insulation (D). For every task the corresponding 'pitches' are calculated (Figure 6). The 'pitches' are used as a measure indicating the productivity to be reached by the installation crews on-site. To control, in a reliable way, if the scheduled amount of work was reached, CAs are further split in CUs. Each CU is defined as the space between two main axes of the building. Considering Figure 6 (task A—installation of brackets), a number of 8 CUs should be completed by a crew composed of two workers in one week. As a result, it allows to measure in real-time the installation process on-site.

$$\boldsymbol{Pitch} = \boldsymbol{JobContent}(\#days, \#weeks)/\boldsymbol{Crew}(\#workers)/\boldsymbol{ConstructionArea}(\#locations)$$

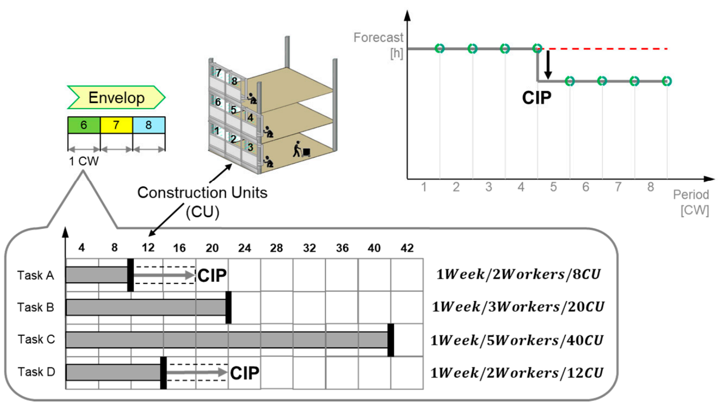

Figure 6. Pitches as enablers for real-time planning and monitoring in ETO construction.

The proposed approach uses 'pitches' as a key performance indicator (KPI) to calculate (and not estimate) the forecast until project completion. By a frequent adaptation of 'pitches' to the real conditions on-site, the erratic assumption of considering a linear relation between time and completed construction locations could be overcome. Therefore, the so-called continuous improvement process (CIP) workshops, taken from lean management theory, are introduced, where 'pitches' are adapted to the real conditions on-site based on past performance (usually 4 CWs). If the 'pitches' could not be reached, related problems, causes and improvement actions have to be discussed and introduced [57]. Otherwise, if the performance increased, due to learning curve effects, the 'pitches' have to be increased and, as a result, the forecast decreases (Figure 6).

5.3.3. Synchronization

Often, the off-site fabrication of elements and the on-site installation are not synchronized, which leads to an inefficient supply chain and stocks. In the proposed approach, production is triggered when the construction site is ready for installation, avoiding intermediate storage. To reach a synchronization of the supply chain to the construction progress, two fundamental preconditions have to be fulfilled: (i) a reliable information of the progress on-site and (ii) a reliable demand forecast.

'Pitching' allows measuring real-time progress and to increase the demand predictability. In brief, to handle the high variances or unpredictable events on-site the 'cyclical planning' is used. It is based on the 'rolling planning' methodology to handle the uncertainty of data in production planning [37]. When the first planning interval is completed, a new one is added. As soon as a complete plan has been generated, no changes are allowed within the 'frozen period' [37]. As a result, this enforces that the planning is followed without rescheduling necessity. However, the construction industry requires a flexible adaptation of schedules to the current conditions. In the 'cyclical planning', a feedback loop is introduced as basis for the following short term planning [58]. According to Figure 4, the scheduling of pitch 2 (t = 2) should be based on the work performed in pitch 1 (t = 1). These short-term scheduling and actualization loops propagate throughout the entire project. Moreover, 'cyclical planning' aims at a self-regulation by means of two control loops. The 'labor control loop' schedules the work to be performed in each period based on the work performed in the previous period. The 'material control loop' triggers the production and delivery of MTO components throughout the supply chain. Referring to the window of predictability on-site, as well as the delivery time of the supply chain, the 'material control loop' considers more than one scheduling period (e.g., CWs) [59]. If labor performance on-site decreases, less material is pulled from the supply chain avoiding an overfilling of intermediate buffer zones. On the other hand, if labor performance increases, more material is requested from the supply chain avoiding an interruption of installation processes on-site [55]. As visualized in Figure 4, the demand variability should not exceed a predefined corridor of capacity flexibility (e.g., ±20%). If the demand variability exceeds it, the project management function should intervene by means of an escalation strategy (e.g., capacity increase by temporary employment).

5.3.4. Process Templates for Planning Configuration of New Projects

Once the complexity of the project increases, the definition of the whole plot goes beyond the capabilities of the human planner. The fourth step 'process templates' consists of identifying processes that can be reused to define new ones. However, some factors exist that may jeopardize the planning of complex construction projects. Firstly, it is necessary to reconcile numerous and highly constrained activities, in an environment with a substantial presence of outsourcing and subcontracting. Additionally, usually workloads are imprecise and milestones are mostly unknown.

To better cope with such situations, Stadtler and Kilger [59] developed the supply chain event management (SCEM) paradigm, integrating the concept of modularity. It grounds on the product breakdown structure, which defines its main functions, the required components and their mutual relations. It is an abstract model in which real modules can be placed according to pre-defined rules. Rules are context-specific and have to be built coherently, starting from the available procedures and knowhow. By using them, the application is able to build rational plans with a minimal interaction of the planners. All the available technical documents, derived from computer aided design (CAD) applications, are gathered to build simple standard elements [60]. Then, the planning of such elements is carried out in detail, assuring that tasks are small and balanced with respect to their workload. Finally, appropriate schedules are defined and maintained as templates for all the standard elements that may be used as models within the planning process.

5.4. Benefits of the Proposed Approach

To sum up, the benefits of the proposed approach in comparison to the traditional methodology are shown in Table 4. Traditionally, the planning functions elaborate the organizational execution planning without integrating the actors responsible for execution on-site. This may lead to schedules that are unfeasible. Further, large job orders are moved throughout the supply chain and on-site, creating high stock levels and long lead times. Conversely, the pitching approach splits job orders into small lots with approximately equal size allowing a reduction of the lead-time and of the levels of stock. Through synchronization of off-site fabrication and on-site installation, MTO components are produced and delivered on-demand. A real-time planning and monitoring of construction projects allows to prioritize the production according to the requests and delays of different construction sites. As a practical example, if construction site A is affected by a building freeze that causes a filled buffer, than MTO components should be produced and delivered to construction site B avoiding high levels of stock and long lead times throughout the supply chain.

Table 4. Comparison of the traditional and the proposed approaches.

Traditional Project Management	Proposed Approach
Centrally managed planning (push)	Decentralized planning (lean pull principle)
Processing of large job orders	Small lots with approximately equal size (lean pitching concept)
Pre-production of MTO components	MTO components are produced and delivered on-demand and just-in-time (synchronization)
Projects are based on individual competencies (project manager, site manager)	A self-control mechanism supports project management
Every project is planned starting almost from new	Process templates are used in a planning configurator

6. Proof of Concept—Industrial Application and First Results

The methodology and IT framework were elaborated and tested in collaboration with an ETO façade supplier company located in Northern Italy. It is a medium-sized company acting as European leader in the delivery of high-class design façades. The case study is based on an expansion project of a city hospital in Northern Italy. It consists of an additional construction of a new clinic composed of three wings (A, B and C) with respectively four levels, and a new entrance area (Figure 7). The case study company played the role of leader company in a bidder consortium responsible for engineering, producing, and installing the façades. The façades were designed by using the mullion-and-transom building technology, where single components are delivered to the site and assembled on the spot. The façade installation started on calendar week CW16-2013 and finished on CW50-2014. The research team had only been involved in the project starting by CW50-2013, because the project manager recognized an exceptionally high consumption of the budget compared to the reached and planned construction progress up to that point in time.

The approaches for process planning, pitching, and synchronization were successfully applied in the case study. First of all, process planning workshops were organized where the project manager, the foreman on-site and the responsible employee of the engineering department participated. The project was structured in CUs, to reach a quantitative measurement of the construction progress. Here, a specific codification was developed which is visualized in Figure 7. It consists of: (1) the considered level (from 0 to 4); (2) the considered wing (A, B, or C); (3) the sun orientation (east, west, and south); and (4) the CU (from 1 to 10). To differentiate between the two types of south façades (according to the façade technology), south façade F (SF) situated on axis F and south façade O (SO) situated on axis O were specified. As a practical example, please consider CU1 of the east façade, wing A and level 0 as displayed in the lower left corner of Figure 7 (0-A-E-1). A CU was defined as the distance between two principal axes of the building. The definition of CUs showed several benefits: (1) every CU has the same size (the distance between two axes consists of 7.8 m; (2) CUs are visible on-site because axes are delimited by pillars; (3) considering façade installation, CUs were small enough to allow a daily measurement of the completed tasks and, as such, a reliable measurement of the construction progress.

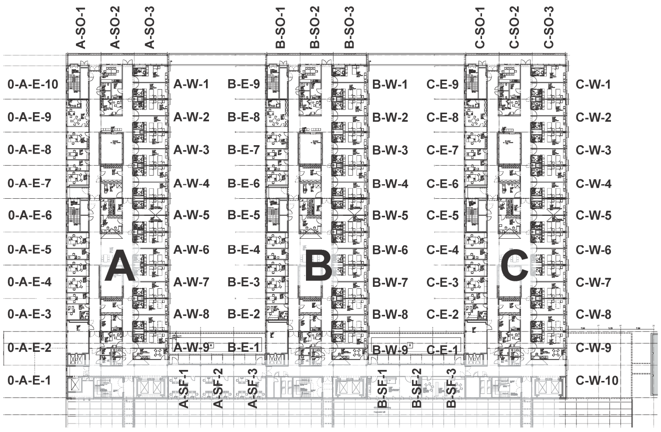

Figure 7. Project city hospital Northern Italy—ground floor with CUs.

Furthermore, a first IT prototype allowing a daily scheduling and control of the installation process was developed. The company decided to perform four CIP-workshops to test and validate the approach (results are visualized in Figure 8).

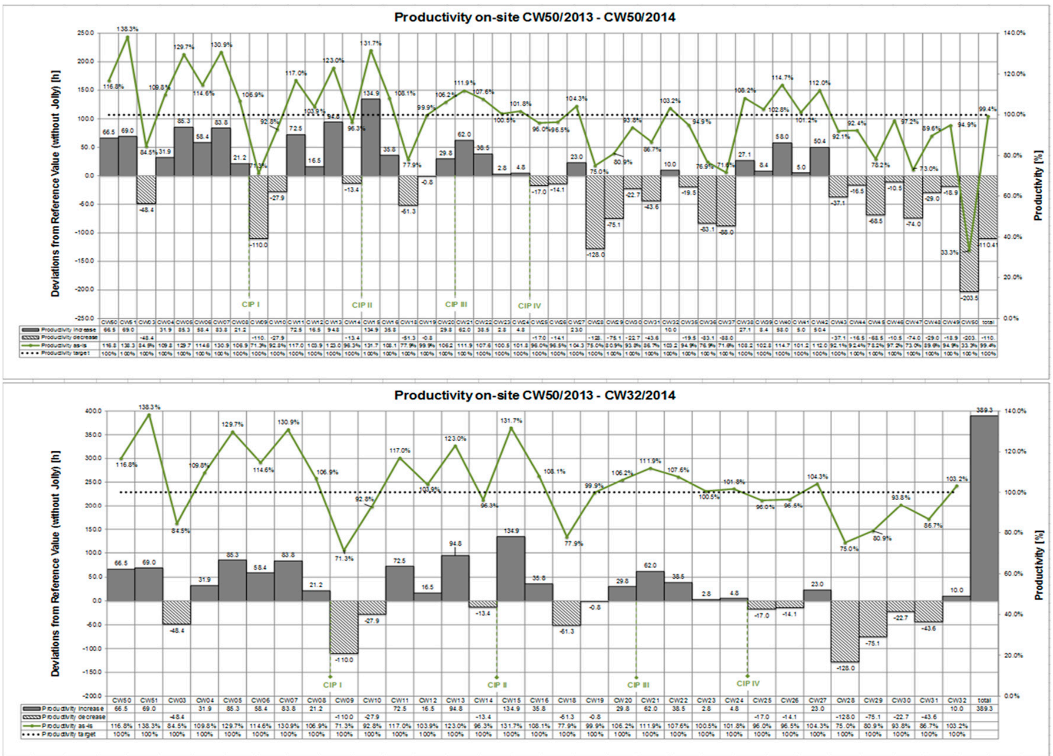

Figure 8. (**Upper chart**) Deviation measurement throughout the entire study period (CW50-2013 until CW50-2014); (**lower chart**) deviation measurement during the application of the CIP-workshops (CW50-2013 until CW32-2014).

Bars visualized in dark gray (positive values) mean an increase of productivity or, in other words, that fewer hours were used as initially planned by using the pitching approach. The crosshatched bars (negative values) visualize a decrease of productivity or a deviation from the pitch. The upper part of Figure 8 shows the deviation measurement of the pitch in a weekly time frame starting from CW50-2013 (December 2013) until CW50-2014 (December 2014). The lower part of Figure 8 shows a snapshot of the CIP-workshops (from CW50-2013 until CW32-2014). More in detail, the first CIP-workshop was held on CW08-2014 (February 2014), the second one on CW14-2014 (April 2014), the third one on CW20-2014 (May 2014), and the fourth one on CW24-2014 (June 2014).

As a practical example, please consider the productivity decrease of −110 h recorded in CW09-2014 after the first CIP-workshop. During this week, twelve workers were present on-site, working from Monday to Thursday 9 h per day and Friday morning 4 h. As a result, an amount of 480 h was consumed from the project budget available for installation. Supporting work, like site management, was named as Jolly and during CW09-2014 an amount of 40 h was allocated to the foreman. A progress of 330 h, according to tasks completed in CUs and considering the pitch as target value, was reached. By comparing the used budget for value adding tasks (440 h) with the reached construction progress in CW09-2014 (330 h) a productivity decrease of −110 h was computed (Figure 8). This productivity decrease was caused partly by engineering errors, like incorrect drillings in the smoke ventilation windows, which caused a rework on-site. Another part could by attributed by the increase of pitches for certain tasks during the CIP-workshop in CW09-2014 because of learning curve effects experienced in the previous interval (from CW50-2013 until CW08-2014). However, as visualized in Figure 8, between the first and the second CIP-workshops there was a steady increase of the productivity on-site which confirmed the practical value of a daily scheduling and control of the installation process and the introduction of CIP-workshops.

At the end of the deviation measurement during the application of the CIP-workshops, at CW32/2014, a productivity increase of approximately 390 h resulted (within 15 weeks). By comparing the lower diagram with the upper one (Figure 8), a drastic collapse of the productivity can be recognized after the last CIP-workshop in CW24-2014 (mid of June 2014). This can be, in part, explained by the fact that, after the CIP workshops, the installation team did not concentrate anymore on reaching the pitches and, therefore, the productivity on-site decreased drastically. As a result, the case study showed that by spending 1 h for applying the approach a working amount of 6 h could be saved (1:6). More in detail, a total forecast decrease of 3700 h corresponding to a labor saving of 8%, compared to the initial forecast, was reached.

7. Implementation of an IT Framework for an Advanced and Digital Application of the Approach

The system view of the proposed IT support is visualized in Figure 9. It consists of three interrelated modules: (1) modeling; (2) scheduling, and (3) actualization. 'Modeling' supports the process planning workshops by digitizing the organizational execution process. In 'scheduling', the work to be performed is planned, and 'actualization' serves as a feedback loop, measuring the project's progress.

The framework is structured in a hierarchical way consisting of three levels, which enable a coordination between and within companies. In level 1 the system view considers the coordination between different companies (master schedule). Level 2 is focused to show the installation process of a specific participating company (on-site). Level 3 provides a detailed view of the installation process on-site and the connected supply chain. Accordingly, the level of detail of tasks increases from level one to level three. Level 3 corresponds to the level of detail that allows to elaborate weekly work schedules on-site and the measurement of the construction progress in a daily frequency. Therefore, the supply chain is connected with this level of detail allowing to request from the construction site the needed components on-demand. The information is reflected to level 2 and level 1, e.g., to consider the delivery time of components in the schedule of level 2 and level 1.

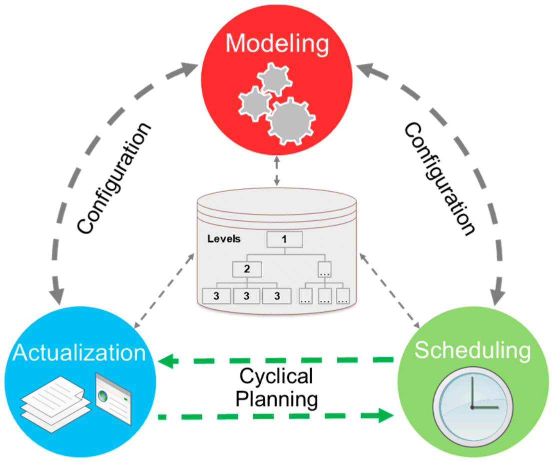

Figure 9. System view of the IT support.

In Figure 10 the pitching and CIP are shown. This describes how the concept is used for real-time process management on the installation site of a single company. Therefore, it covers level 2 and level 3 of modeling, scheduling, and actualization. Due to the fact that the IT framework should work as a tool to support the coordination process, special emphasis is given to the actors involved and their interaction with the IT tool.

First of all, the project manager configures the IT tool by inserting key information of the project, like its duration and budget (level 2). Next, during the process planning workshops the CAs are defined and tasks (like task A—installation of brackets) are assigned (level 2). For every task, logical dependencies are defined and the necessary workforce is specified. Finally, the task duration (in days) is estimated by the participating experts.

At this point, the application computes the pitch per task according to Figure 6. According to it, the IT tool calculates the total effort per task and, if it is greater than budget specifications, the duration should be revised by the process planning participants. Otherwise, the cyclical planning (scheduling and actualization) by the foreman on-site can start (level 3).

The foreman on-site chooses the CIP length (i), i.e., the period where a detailed monitoring of the construction progress is performed (e.g., 4 CWs). During this period (CW1–CW4) the foreman on-site elaborates the schedules and controls in detail the daily feedback of the different installation crews. If the pitch was not reached on the installation site, an appropriate problem is recorded.

When the CIP-length is over, a CIP-workshop takes place (level 3), where both the foreman on-site and the project manager participate. The IT tool aggregates the daily actualization in a weekly overview and calculates the deviation from the pitch (e.g., in hours). If the deviation is less than zero, it means that less effort was used to perform a task than initially scheduled (according to the pitch). As practical example, according to Figure 6, for task A—installation of brackets, a number of 8 CUs should be completed by a crew composed of two workers in one week (2×40 h/week = 80 h $\rightarrow$ 10 h/CU). If the crew was able to complete 10 CUs per week a work saving of 20 h could be reached. In this case, the IT tool should suggest an increase of the pitch to 10 CUs/2 workers/week. During the CIP-workshop the foreman and project manager decide if the event was just an outlier or if the pitch could be increased. In this case, a recalculation is performed (according to Figure 6) resulting in a decreased forecast. On the other hand, if a positive deviation resulted, the registered problems should be analyzed, to identify the causes and to define the countermeasures. If no countermeasure could be defined (e.g., recurring bad weather conditions), than the pitch for a specific task should be decreased and the forecast should be recalculated resulting in an increase. This loop iterates until project completion. The process is described by means of business process model and notation (BPMN) and visualized in Figure 10.

Such a structure is particularly suitable for a web-enabled, collaborative, and distributed IT architecture [61,62]. This applies naturally to the planning stages, where the availability of good shared knowledge is necessary to build feasible and effective plans [63], but becomes almost paramount when dealing with the 'cyclical planning'. This means that the monitoring stage, which is intrinsically facilitated by the pitching process, may further benefit from the presence of a web-enabled software application. The previous affirmation is supported by a number of aspects and evidences, among which it is important to cite the followings:

- The distributed environment is coherent with and fostered by the present advances in the Industry 4.0 implementation. These new scenarios push communication requirements, data interchange capabilities, and the real-time planning up to the limit;
- Exceptions and delays in the scheduling are immediately communicated to all the involved actors, providing an effective "early-warning" control system, and allowing to adopt the right countermeasures in a timely manner;
- Events and responses are correctly managed and registered within the system, assuring that no knowledge is lost;
- Changes in designs and plans are generally available and always up-to-date;
- Data are properly maintained and no duplication occurs; and
- The shared environment helps overcoming the limitations imposed by the presence of numerous and different software tools.

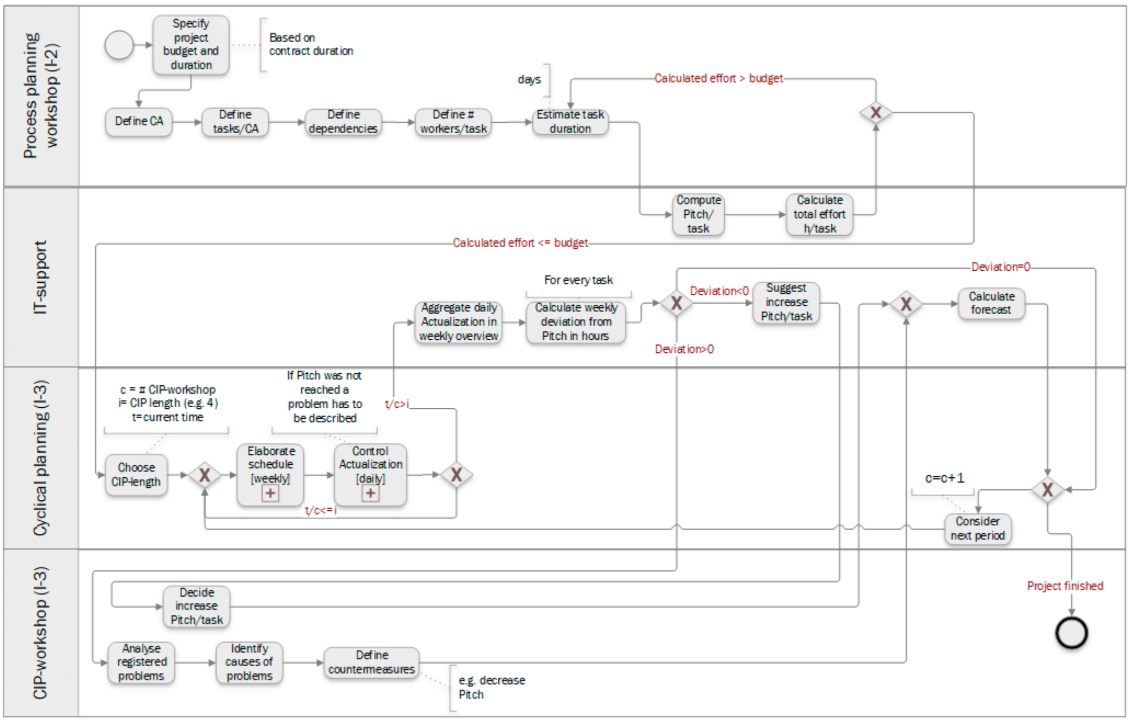

Figure 10. Process of IT support 'Modeling-Scheduling-Actualization' with BPMN.

8. Conclusions, Limitations, and Further Needs for Research

To answer the research question, the pitching approach from lean management was introduced to the construction industry. Furthermore, by using the pitching concept to schedule and control the physical locations (CAs) of the building, a real-time measurement of the construction progress and a reliable demand forecast become possible. More in detail, by introducing the lean CIP-workshops and adjusting the pitches (as performance targets) at frequent intervals to the real conditions on-site, the erratic assumption of conventional methodologies, which consider a linear relationship between time and completed CAs could be overcome. For a correct monitoring and forecasting of the construction project, the progress should not only be evaluated with respect to the planned activities, but also mainly in terms of tasks completed in construction locations and the used labor amount according to budget specifications. In this way, the controllability of construction projects can be increased because potential problems are identified early on and improvement actions can be implemented in time.

The limitation of the presented approach is that up to now it was mainly applied in repetitive façade construction projects. It has been shown, that by using physical locations of the building (called construction units, CUs) a quantitative and reliable measurement of the construction progress becomes possible. However, considering non-repetitive construction projects, where the technological content and the job amount varies between different construction areas of the building, it is not possible to measure the construction progress by using physical locations. Currently, the research team started to collaborate with a heating, ventilation and air conditioning (HVAC) construction company to adapt the pitching approach to non-repetitive projects. First, results have shown that, by using specific measuring units for tasks in construction areas (like pieces, square meters or running meters), instead of using just CUs, a reliable construction progress measurement becomes possible even in non-repetitive projects. Another limitation of the presented research is that, up to now, it was applied only to the envelope construction phase (façades). More in detail, it was applied to the intra-company coordination or, in other words, the synchronization of off-site fabrication with on-site installation. Furthermore, logistic disturbances in terms of variabilities in transportation processes from manufacturing to the installation on-site were not considered. In the presented case study (hospital expansion project) the installation site was near to the fabrication shop and, therefore, logistic disturbances could be neglected. However, if there are large geographical distances between fabrication and installation, transportation processes have to be considered in planning and releasing the right material to construction.

In the following paragraph, the generalization of the findings to other cases is presented. To reach reliable and detailed schedules (the level of detail of tasks), those responsible for execution (foremen) should be involved in the planning process. To allow for reliable short-term scheduling and real-time monitoring the pitching concept should be used. The pitching concept uses information about the right number of workers needed to perform a task and how many CUs should be completed in a specific time interval for not overrunning budget specifications. In future research activities the appropriate level of detail to define tasks and pitches for trades working in the skeleton and interior construction phase will be investigated. By using pitches in monitoring, a reliable and quantitative measurement of the construction progress is possible. Although, the level of detail to define CAs is different in the skeleton and interior construction phase. Considering the skeleton construction phase, CAs could be defined in sectors as different and independent parts of the building (like wing A, B, and C in the presented case study) and levels of the building. However, in the interior construction phase the degree of detail of level would not be enough and therefore within every level different sections should be defined. As practical examples, the section corridor or sleeping quarters could be mentioned. Moreover, scheduling and monitoring should be performed in short time intervals allowing a flexible and fast reaction to variances on-site (cyclical planning). In the presented case study of the city hospital expansion project a daily scheduling and monitoring of façade construction was applied. However, for trades working in the skeleton construction phase, the right frequency for triggering a cyclic planning (e.g., daily, weekly) has to be investigated and might be different from the one used in our case study for façade installations. To avoid budget overruns due to missing material on-site, the supply chain should be triggered according to the construction progress. Here, two strategies are proposed: (1) if the delivery time enters the window that allows a reliable prediction of tasks to be completed on-site, the production start can be triggered directly by the cyclical planning; and (2) if the delivery time does not enter the window of predictability on-site, fabrication has to be triggered in advance and products have to be released from an intermediate inventory (buffer on-site or at the fabrication shop).

However, to roll-out the approach effectively in practice, an appropriate IT framework has to be developed. During the expansion project of the city hospital project a first IT prototype was developed according to the IT framework and tested in practice. Its first application showed a promising potential in terms of a better control of the available budget for installation on-site and for synchronization of the supply chain, avoiding installation interruptions due to missing materials. Future research is focused on extending the developed methodology and the IT framework to reach an effective intercompany coordination between different trades. Here, the presented approach will be adapted to be used by trades working in the skeleton (like masonry) and interior construction phase (like HVAC). Further research is focused to synchronize the coordination within companies (intracompany) with the coordination among different companies on-site (intercompany). Moreover, transportation processes from manufacturing to the site will be considered, to handle logistic disturbances appropriately in the approach and the IT support. In conclusion, the IT prototype will be improved by applying it in different case studies from the skeleton, envelope, and interior construction phases to reach an appropriate acceptance level of the involved construction workers as basis for a future commercial software development project.

Acknowledgments: This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 734713.

Author Contributions: P.D. developed the lean approach for real-time planning and monitoring in ETO construction projects; M.F. contributed with his expertise in the field of MTO production and lean management; and E.R. contributed with his expertise in the field of lean methods, production planning, and control in manufacturing.

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

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