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Lean and Flexible Project Delivery

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Abstract: The average cost and time overrun of frequent changes in ETO and construction projects is high, and with steadily increasing cost constraints, productivity increase is critical for future competitiveness. Successful lean implementations in project-based production systems have led to great reductions in waste and time to market. However, companies also often struggle with effective customization of lean principles to their changing contexts. This paper extends the scope of the operational system of lean project delivery, initially focused on a project-based production system with the Last Planner System (LPS®) at core, to enhance master planning with options to flexibly handle changes. The research follows the guidelines of Design Science Research, combining the theory and practice of lean project management with results for project flexibility from quantitative models. The main contribution is the proposed operational system, along with the process to evaluate its intended utility, i.e., to increase the ability to quickly and cost effectively handle late changes. This enables the quantitative assessment of the value of planned flexibility in lean projects, before the decision is taken, and illustrates this value for capturing opportunities from customer-driven changes. Insights into the value of design research for the management of project uncertainty are emphasized.

Keywords: project uncertainty; engineer-to-order; lean project delivery; Last Planner System (LPS®); flexibility; design science research

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1. Introduction

Engineer-To-Order (ETO) and construction projects are subject to impactful uncertainties that are difficult to anticipate and quantify early [1–6], driven by, e.g., uncertainty in the market and technological innovations, leading to changes in design, with subsequent alterations in the activities and their sequencing [7]. In ETO shipbuilding, this can be everything from changes in scope outfitting (e.g., the engine type) to door and window positions, also generating changes in piping and electro solutions [4,8]. While limited predictability, the strategic intent (e.g., to capture opportunities from customer-driven design changes) suggests that changes will come to provide competitive advantage to that organization at that time. The exact type of a change is difficult to estimate though. Such 'knowable unknown-unknowns' [9] are most often managed reactively [10,11], bringing overreliance on determinism in project research [12], with important decisions and activities fixed early [13]. These are necessarily updated in light of new information [14], but often with large reaction costs [7,8,15], and without the ability to sufficiently exploit uncertainty to improve project value [16,17].

With increased understanding of the cost of neglecting project delivery capabilities to explore opportunities [18], the negative impacts of design disturbances [19] and information inadequacy [20], resilient approaches [21,22] and options for flexibility are increasingly sought after [20,23,24]. This is not new though. Between [5], on how project management transited from flexible approaches (e.g., the Manhattan project in the 1940s) to control-oriented phased approaches, to summarizing over resilient project delivery strategies in [25], we have Chapman and Ward [17,26], highlighting that conventional project research with focus on risks has limited ability to capture opportunities.

Flexibility, i.e., the ability to change the direction of the project within defined time-cost frames, implies the existence of an operational strategy and a planning system that is responsive and handles information arrival and delayed decisions simultaneously [7,15,27]; i.e., a system with options. Otherwise, new information has limited value, as it would not exploit the threats and opportunities that lie in, e.g., allowing customers to make changes. Options for flexibility are to be paid early, while their value is not revealed before changes are materialized, often in the late execution phase [28], which is why flexible approaches are often countered with economic arguments [5]. This cost-value structure of systems with options implies a change in the value creation locus, and the need for life-cycle approaches with a new logic of business models [16,29].

One integrated approach is found in [30], with a project management information system for integrated planning, scheduling, and communication, facilitating collaborative and immediate information sharing. While effective to quickly adapt new information, that is not a system where options for flexibility are explicitly implemented. In general, integrated life-cycle approaches to project delivery are few [3,21], and consequently, predictive evaluations of the quantified impact of late changes are rare too [21], and option less valued. Further, the few papers that quantify the value of planning flexibility [8,31] are based on small examples that are difficult to be applied in practice. The learning from these models, on what flexibility and when to develop, has managerial value though. To transfer this learning into practice, lean construction with integrated and lean project delivery at core [32,33], emerging from the shortcomings of phase-based approaches [2,11,34,35], is found appropriate. The lean philosophy adopted in these, combining formal and less formal processes, plays an important role in collaboratively organizing projects to better handle disturbances and to foster innovation [36–38], disrupting the logic of the business models for how the construction industry delivers projects [39]. Further, flexible set-based design principles [40], as an essential element of lean construction, support generating multiple solutions to changing conditions. Moreover, a new lean metric is also proposed in [28], named the Overall Construction Productivity (OCP), to quantify the impact of identified losses in ETO production systems, and to guide the implementation of improvement actions. What is missing from this framework is an operational strategy and planning system with guidelines to flexibly implement alternatives to reduce disturbances and losses in late phases in lean project delivery, and to quantify the value of flexibility. The paper at hand fills this gap by addressing the following research questions:

(1) How to incorporate options for flexibility into project master schedules within the lean project delivery?
(2) How to ascertain what is the 'right' level of flexibility to appropriately address risks and opportunities, and how to measure its value?

The novelty is driven by the new knowledge that the research enables by combining different and largely disconnected research fields, such as lean project management and guidelines for project planning flexibility from model-based research. The novel elements are: (1) extending the operational system of lean project delivery—the Last Planner System (LPS®)—to master planning with options, to enable ETO organizations to customize lean construction practices to their dynamically changing uncertain contexts; (2) predictive evaluations of the quantified impact of late changes and the value of flexibility in lean projects; which also enables (3) to more appropriately deal with opportunities resulting from customer-driven changes (an almost overlooked aspect in project research and practice).

The paper is structured as follows. Section 2 outlines the theoretical and methodological approach, Section 3 describes the operational system for lean and flexible project delivery, with valuation of planned flexibility and discussion by case tests in Section 4. Section 5 concludes by providing insights the proposed solution and methodological approach add to the management of lean and uncertain projects.

2. Materials and Methods

The aim of this research is to develop new knowledge that professionals can use to design good solutions for managing complex construction and ETO projects under uncertainty. Design Science Research (DSR) is found appropriate for this purpose, with contributions from different scientific disciplines, combining the theory and practice of lean project management with multi-stage thinking from decision theory and guidelines for flexibility in ETO projects developed by stochastic optimization, as well as bringing in practitioner experience. This supports [41] in that construction management research can be characterized as a multidisciplinary design science, with outputs from empiricism, normative approaches that specify what to do under given circumstances, and insights into the interrelation between design, production, and operation of the built environment. In this section we introduce, first, the theoretical lens on what the chosen perspectives bring into the new solution, and second, the steps in the methodological approach.

2.1. Theoretical Lens

2.1.1. Project Uncertainty

What counts as important for uncertainty assessment in a planning perspective is its predictability [7–9,42]. Predictable uncertainty (knowable-unknowns [9]), such as variation in activity duration, is the most frequently studied source of uncertainty in project planning [31], anticipated and described statistically, and often handled by buffering around the critical path [43]. This approach, while widely used, may generate unnecessarily long project timelines and may not prevent the propagation of uncertainty through the schedule [44]. A different source of uncertainty in ETO, building construction, and new product development projects is changes in project scope, design, and technical specifications. The market characteristics, technological innovations, or regulatory interventions often dictate the occurrence of such changes, but with difficulties in predicting the exact type and size of a change [4,8,31,42]. Such 'knowable unknown-unknowns' [9] may lead to alteration in the project network itself, not only in the duration of predefined activities [7,31]. Hence, buffering has limited value, as we do not know where and how it is needed. The impact hierarchy of these types of uncertainties is quantified through small stochastic optimization problem instances in [8], pointing to uncertainty in design as most influential for planning ETO projects, dictating what flexibility to develop and where.

A second aspect of importance for our uncertainty assessment is the distinction between negative and positive sides of uncertainty, insufficiently exploited in project research and practice [2,16,20,21,42,45], overly focused on risks and with limited ability to capture opportunities [17]. Opportunities arising from changing market conditions usually have a defined customer value and 'market price' for the change, primarily driving profit, as opposed to risks, primarily driving costs. What is important to understand is that the different objectives of risks and opportunities imply distinct solutions, with potentially distinct options, which are to be developed in early project phases. Once the options are enabled, both situations turn into cost-focus to deal with emerging changes then-and-there, with least costs and disturbance. The exploitation of an opportunity requires, hence, significantly different approaches than simply scaling or buffering a baseline plan [7,46].

In project-based production, the net benefits of use are the results of subtracting whole life costs from whole life benefits [36]. In that framework, the fundamental meaning of a threat is the risk of reducing net benefits in use, which can occur either from increasing costs or reducing benefits. Opportunities offer possibilities to increase net benefits in use, which can occur either from reducing cost or increasing benefits. The knowledge needed is centered on ways to reduce costs without reducing benefits, and to increase benefits without increasing cost beyond the target ratio. In conditions of uncertainty, what counts as net benefits in use to a client may change during the project, or events may occur that necessitate a change in the pathway to targeted net benefits in use.

2.1.2. Resilient Approaches to Project Uncertainty

Resilient responses to project uncertainty date back to the 1940s [5], with increased consciousness to differentiate between risks and opportunities in [17,26], to borrowing from the agile [25] and operations strategy literature [18] in order to emphasize project delivery capabilities to provide competitive advantage by, e.g., exploring opportunities through customer-driven design changes. Our research falls, hence, within the scope of [18].

Managerial questions to answer when engaging with options for flexibility are how much, how to enable it through the project delivery, and how to measure it. On the first one, from option theory we know that higher uncertainty in the payoff implies higher levels of flexibility and higher value of flexibility [47]. On the other hand, lower levels of flexibility are shown to nearly capture the benefits of full flexibility [48], and high operational uncertainty may reduce the value of options [49]. The second question has been mainly explored in operations strategy in the agile community as a whole, from design projects and job-shop scheduling [50], with the Toyota lean product and process development as one successful example [40,51] (which also motivated the lean construction environment to adapt lean from repetitive production), to portfolio management and assortment planning [52,53]. In project planning, valuations of planned flexibility are few and largely based on small examples [8,31]. The stochastic program in [7] helps with the understanding of how design flexibility adds value to the project and how to decide for the 'right' level of flexibility. In that paper, the reported cost improvements are up to 35% as compared to reactive deterministic approaches. The stochastic programs in [7,8] are not for large applications (due to the complex uncertainty and dependency patterns involved [14]), but these works enable conceptual learning and understanding on the quantified value of planned flexibility and provide examples on how to operationalize design alternatives in project planning.

2.1.3. Lean Project Delivery and Practitioner Experience

Lean project delivery initially focused on a project-based production system to support a new and better way to design and build capital facilities, with the Last Planner System (LPS®) at the core of its operations [33]. LPS®—the first widely adopted approach for design and construction management since the critical path method—has justified its implementation by making significant improvements in cost, time, and quality [33,36,37,54–56]. It builds on the acknowledgement that well-designed processes are both technical and social [33,57], with social skills built on commitment and trust, and knowledge of who has the relevant competence and responsibility to perform an activity. This contributes to a decrease in uncertainty [58], facilitates sharing and combining resources, and facilitates high performing teams [1,59,60]. Further, it fosters a decentralized collaborative planning environment to exchange progress and to continuously resolve constraints, with decisions delegated to the lowest level in the planning hierarchy.

That said, this process requires adapting to new information from the standpoint of progress made in the project, which may or may not cause a disturbance based on measures taken to prepare changes. LPS® has not previously explicitly addressed objectives or pathways that may change during the project, nor options to flexibly handle these, apart from advising master plans to be kept at the milestone level between project phases, and planning in greater detail as the time for execution approaches [42]. On the other hand, the responsive and collaborative social capabilities of LPS®, along with its wide adoption in the Architecture, Engineering, and Construction (AEC) industry, provides incentives to explore planning flexibility within this framework.

To strengthen our motivation to explore flexibility within lean project delivery, below we highlight practitioner experience on current and future-state master planning, documented through interviews with architects, master planners, project managers, and lean consultants from two categories [61]: "*Traditionalists who perform their services in the old way* (*one described it as "... our process is very 1980's"*) *and Innovators who are frustrated with the limitations of the old way and are working to improve master planning processes and outcomes*".

The shortcomings of "old" approaches to project uncertainty (still used by most construction projects [62]), as seen from Innovators' perspective, are related to, e.g., organizational and contract issues that hinder integration across project phases and functions, the risks of the unpredictable, distrust, fixed-fee master plans, and master plans which pass knowable risks along the design and construction phase, unmitigated, where the impact is more damaging. The Innovators' answers to these include a large list of established lean strategies (e.g., collaborative concept phase planning with focus on life-cycle optimizing the whole project and team learning), and new solutions such as adapting Last Planner to master planning as a process for not only scheduling work but also for identifying constraints and mitigating risks. Other innovative solutions juxtapose approaches such as just-in-time decision making, rapid prototyping, and set-based planning to evaluate combinations of multiple alternatives. These solutions, while largely ad hoc and experience-based, provide additional support for claims earlier in this paper regarding gaps in literature with respect to managing project uncertainty.

2.2. Methodology

We applied Design Science Research (DSR), " ... *fundamentally a problem solving paradigm*" [63], with a research process that emphasizes learning through prototyping by build-evaluate. learning loops, to gain understanding that is only achieved through cycles of design-construction [64], until the prototype serves the artifact's intended purpose [63]. DSR is traced back to [65,66] and has been applied to different fields of management [67], such as information systems design [68], organizational development [69], operations research [70], operations management [71,72], and construction management [73].

One of the most important activities in DSR is evaluation of the performance of new solutions, with questions on what and why to evaluate, and when and how to evaluate. This connects to how well the artifact performs in relation to its scope, and it is tightly coupled with the artifact design itself. The DSR literature provides little guidance to which evaluation methods to use, why, and how to use them. The authors of [74] propose to distinguish between ex-ante vs. ex-post evaluations, or qualitative vs. quantitative. Ex-ante assessment is found appropriate under substantial uncertainty [74], as it is the research at hand.

We followed the DSR model in [70], adapted from [75], with: Step 1, awareness of the problem and the theoretical lens (Section 2.1), with a summary of what the chosen perspectives bring into the new solution in Table 1; Steps 2 and 3, the artifact design and its evaluation, a build –evaluate learning loop until the solution is customized (in terms of the appropriate level of flexibility) to provide expected competitive advantage (Sections 3 and 4); Step 4, assessment of the solution in relation to what it adds to the knowledge base of managing project uncertainty [74] (Section 5).

Table 1. What the chosen perspectives bring into the new solution for lean and flexible project delivery.

Lean Construction	Decisions under Uncertainty, Stochastic Optimization	Practitioner Experience
-Collaborative integration of phases and stakeholders, -LPS®, -PULL planning, -Last Responsible Moment (LRM), -Team learning, team responsiveness, -Lean/set-based design, -Control is proactive and reactive.	-Guidelines for flexibility assessment, -Options for flexibility, -Multi-stage decision process, -Minimal information needed for decisions, -The quantified value of proactive vs. reactive planning, -The impact of design changes, -The impact hierarchy of multiple uncertainties, -Control is proactive and reactive.	-Lean strategies, such as collaborative concept phase planning and team learning, -Just-in-time, -Rapid prototyping, set-based planning, -Continuous risk assessment and mitigation through the project, -Adapting LPS to the entire project.

3. Results—Lean and Flexible Project Delivery: LPS® with Options

The main result of this research was the extended LPS® with options to enable flexibility in lean project delivery, as described in this section. This answers the first research question. The development of the operational system proposed below is tightly intertwined with the valuation of its intended utility, to increase the ability to quickly and cost effectively adapt changes. This is described in Section 4 and answers the second research question. At the heart of the lean philosophy is the lean ideal: to deliver ever more value with ever less waste. Increasing project flexibility is in the service of the lean ideal, so we are proposing to add to the lean tool kit.

What we advocate here is a proactive-reactive operational system that combines the established lean principles of LPS® with up-front practices to implement options for flexibility in master planning. Incorporating options raises, first, the question of how to set milestones to pursue objectives and implementation pathways that may change during the course of the project, and second, how to connect these to the established LPS® operational system. One important issue in this regard is to enable the co-existence of alternatives and condition their selection on the arrival of information. This is related to multi-stage thinking in decision theory, with stages defined by points in time when potentially useful information becomes available and when it is also feasible to update a decision. Feasibility is defined by the Last Responsible Moment (LRM) to make a decision, and the minimal information needed to make that decision.

We applied pull planning to the first draft master plan in a backward fashion and embedded options at the milestone level in a forward fashion. Pull techniques, doing only that work which is needed and when it is needed, increases value generation in the project. We worked backward from a target completion date toward the milestones so that the completion of these milestones releases new ones in a backward direction.

Uncertainty is assessed by the impact of potential disruptions in a system perspective, without concern on probabilities, in the spirit of [76] with proposed adoption to ETO shipbuilding in [77]. The latter combines the Design Structure Matrix, used to analyze technical relations between design activities [78], and the SFI system of coding of ships [79], to map iteration, rework, and information exchange loops if disturbances occur. Combined with life-cycle costing, this approach helps to quantify the impact of disturbances, and removes the need to deal with probabilities where this is not possible or makes little sense, and enables the developing of buffers and flexibility strategies at the right places.

For high-impact uncertainties (in terms of rework needed, but disregarding the probability of occurrence), options for flexibility were embedded into the first draft pull plan. This is undertaken by staging the planning process with respect to information arrival for the uncertainty at hand and feasibility assessment. Guidelines on where and what flexibility to develop from [7,8] were considered.

This planning process requires coordination and interfacing with stakeholders, to continuously align information arrival and material flow with stakeholders' and project delivery capabilities.

The steps in the proposed system are listed below, with their interrelations presented by Figure 1:

1. Implement a collaborative approach to define project value with accepted time-cost-risk estimates;
2. Develop a first draft master plan by applying lean principles for pull planning in a backward fashion from a selected completion date;
3. Assess project uncertainty, by the impact of changes in a systems perspective, disregarding the occurrence probability;
4. Manage uncertainty, by distinguishing between predictable and less predictable high-impact disruptions (where options may be needed);
5. Validate the project with the chosen level of flexibility, i.e., assess the value of the master plan with and without options, to prove with limited knowledge whether the project satisfies the goals from Step 1; adjust the goals or the plan (level of flexibility

and/or buffers). Implement build-evaluate. learning loops of Steps 1 ÷ 4, until the accepted trade-off between costs and benefits of flexibility is achieved;
6. Apply the established LPS® project control schedule (as described below) to progressively detail the alternative implementation pathways, to enable the selection of alternatives as execution approaches in time and relevant information is revealed.

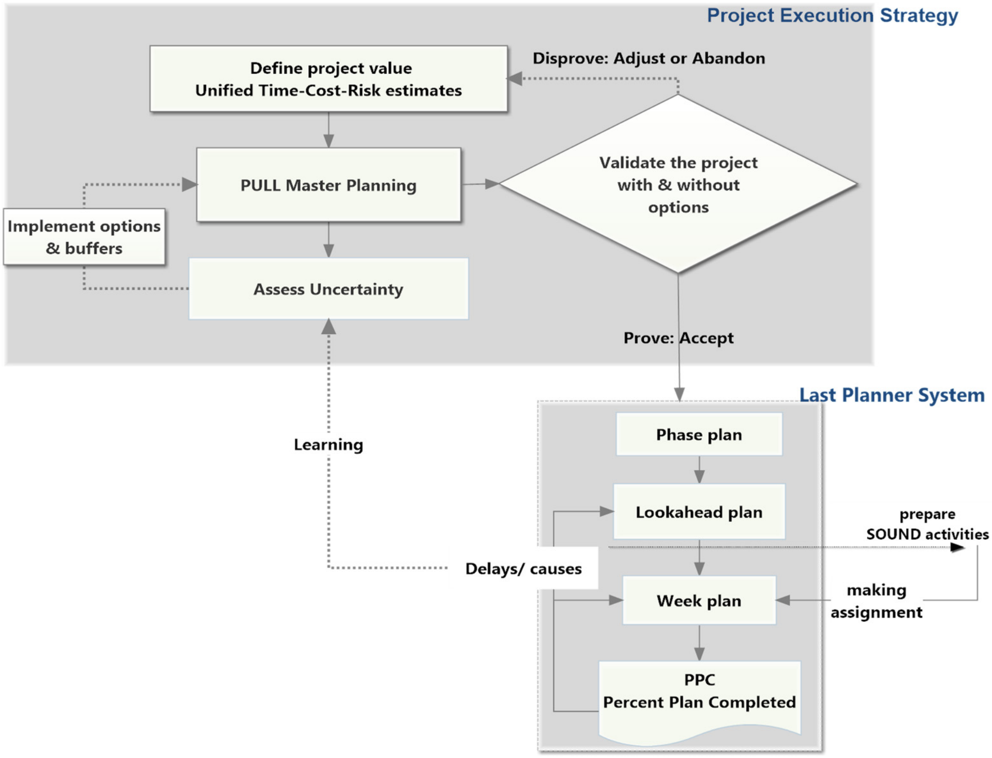

Figure 1. The extended LPS operational system with master planning with options.

Lookahead planning aims to make scheduled tasks ready for implementation through constraint removal so that they can be performed when scheduled. In case of a potentially impactful change, lookahead planning necessarily involves alternative implementation paths, as enabled in master planning. Commitment plans are formed by selecting from activities ready for implementation, expressing what will be undertaken in the plan period. Plan failures are analyzed to develop countermeasures for preventing reoccurrence of failures.

The LPS® social practices facilitate team responsiveness so that smaller changes are effectively dealt with by the means at hand.

The predominant metric in LPS®, designed to measure and manage the health of the planning and control system, is the Percent Plan Complete (PPC) [80]—the share of completed work from what is committed to be completed (i.e., PPC = did/will). Other metrics are Tasks Anticipated (TA) and Tasks Made Ready (TMR) [36]. With the extension of LPS to master planning with options, new metrics connected to the milestone variance and commitment levels are necessary and discussed in [81].

4. Discussion—The Utility of the Proposed Operational System

The intended utility of the proposed operational system is to increase the ability to quickly and cost effectively adapt changes. This is demonstrated by the value of flexibility enabled by the new approach, measured by the expected cost and time savings while delivering customer change. The evaluation process enables the comparison of the utility of different solutions, without and with flexibility, before the decision is taken. The evaluation process is intertwined with the planning process in Section 5, through build-evaluate. learning loops of different levels of flexibility, until the new solution is aligned with accepted performance estimates. As such, the proposed operational solutions provide guidelines for project validation under limited (design) knowledge, an essential part of integrated project delivery in lean construction [82].

The evaluation process is described by, first, using experimental data from [7], and second, real case data from [61] to illustrate the potential gain by exploring opportunities through the proposed planning approach. The research is a proof of concept that requires true validation applied by practitioners.

4.1. The Evaluation Process and Project Validation under Limited Knowledge

The utility evaluation process is developed through a small planning problem in ETO shipbuilding from [7,8], with practical interpretation in [8] " ... *re-outfitting existing ships with competing technologies, e.g., diesel electric or diesel electric-hybrid propulsion systems. Hybrid technology provides high-efficiency alternative applications in some cases, by storing electrical energy in rechargeable batteries, but its compatibility with existing solutions on one-of-a-kind specialized projects is an acknowledged challenge. It turns out that one solution alternative (e.g., fully customized or modular) is better, with shorter expected duration than others (i.e., negatively correlated), although substitutable. This understanding only becomes available after collecting information, in our case after re-opening the ship, often far into the re-build process with a chosen solution*." There, the problem is modeled and solved by stochastic dynamic optimization for different levels of uncertainties and different datasets built to reflect true challenges. For the scope of our paper, we arbitrarily selected planning scenarios with optimal solutions from [7].

Consider master planning with uncertain engine design, with possible outcomes A or B. We assume that the subproject consists of activities piping (P) and electro (D), as PA, DA and PB, DB for designs A and B, respectively, and activity K which is independent of the design choice. Further, assume that the design-dependent activities can follow two implementation paths: (1) specialized for design A or B from the start (i.e., P0A, D0A and P0B, D0B); and (2) flexible, with first-stage activities P1 and D1 standardized over both designs, and second-stage activities customized to real customer preference, P2A, D2A and P2B, D2B, respectively.

The planning horizon is 11 periods, with information about the preferred design available in Period 4. "Wrong" activities are undone, with durations equal to the corresponding activities, as follows:

Activity	P0A	P0B	P1	P2A	P2B	D0A	D0B	D1	D2A	D2B	K
Duration	4	3	3	2	1	3	4	3	1	2	2

Two resources are available per period for the unit cost 1.0, a third one can be acquired for 1.5, and a fourth one for 2.0.

4.1.1. The Evaluation Process

The steps for project validation are illustrated by the flowchart on Figure 2. First, we evaluate the performance with full information, under the assumption of design A (Case 1). Second, that plan is updated to design B, which is what the customer prefers at Period 4 (Case 2). Third, the performance of a lean plan through pull planning is evaluated, with uncertain activities postponed until information on preferred design becomes available in Period 4 (Case 3). Fourth, we evaluate the performance of a proactive approach, where uncertainty is accepted and handled by a flexible strategy to enable adaptation to whatever the preferred design turns out to be (Case 4). Finally, the performance (durations and costs) of the different cases is compared (Table 2), and structural differences between the planning approaches are discussed (with optimal plans shown by Figure 3 in Section 4.1.2). This ex-ante evaluation process is leading to informed decisions in terms of expectations in cost and time.

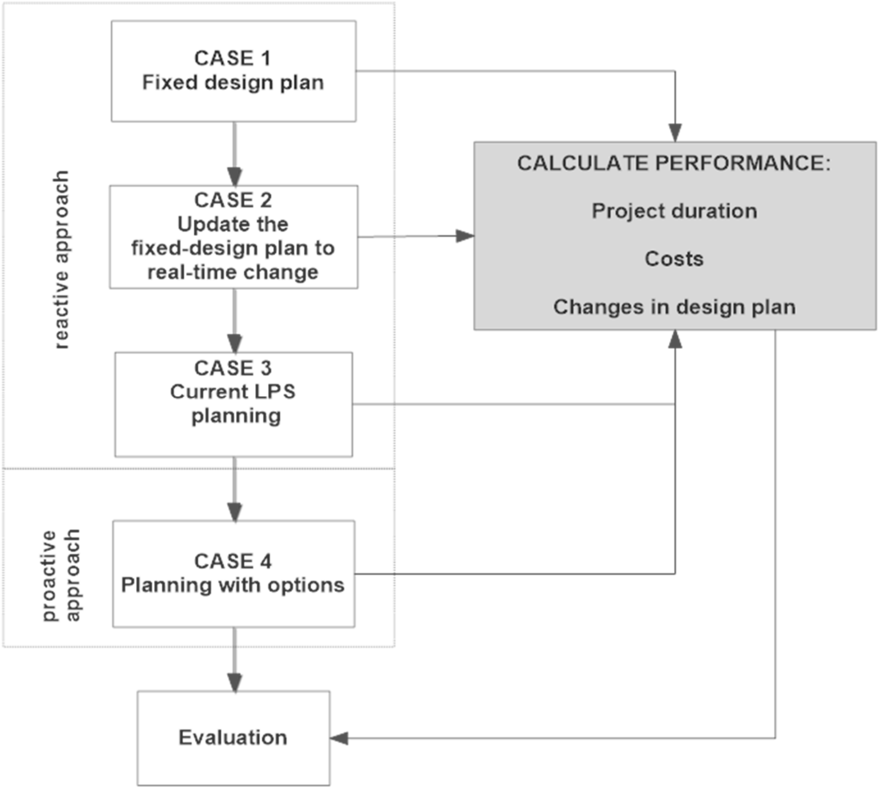

Figure 2. The process of project validation under uncertainty.

Table 2. Comparing different planning approaches to handle the uncertainty at hand.

Planning Strategy	Duration	Costs	Decision Maker
Case 1—Fixed design (A) plan	5	9	Believes to end up with this performance,
Case 2—Reactive approach (Update Case 1 plan to design B)	11	23.5	but will end up with over 100% increase in time and costs.
Case 3—Lean approach	8	9	Postponement and buffering.
Case 4—Proactive approach with options	6	11	Flexibility to adapt changes with least time and costs.

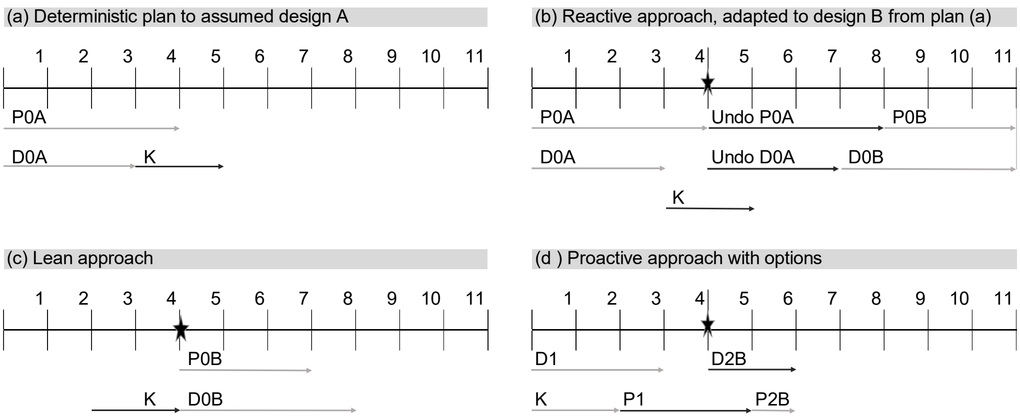

Figure 3. The optimal plans under the four planning approaches: (**a**) Deterministic planned to assumed design A; (**b**) Reactive approach, adapted to design B from A; (**c**) Lean approach; (**d**) Proactive approach with options.

4.1.2. Evaluation of the Different Planning Approaches

As shown in Table 2, the best possible result (with duration of 5 to a cost of 9) is achieved under (assumed) full information, with the corresponding plan in Figure 3a. This plan leads to substantial rework when the design is different from the assumed one (see Figure 3b), with over 100% increase in time and costs (duration of 11 to a cost of 23.5). With resources available for an extra cost, the overall duration can be reduced from 11 to 10 (still 100% increase as compared to the best possible) but to an even higher cost of 25.

Further, in Case 3, postponement and reaction to real-time information (at Period 4) combined with buffering is applied, in the spirit of lean. The time before Period 4 is filled in with activity K that carries no uncertainty. The corresponding plan (Figure 3c) provides a completion time of 8 to a cost of 9, with a schedule buffer of 3 (sized to design B) as compared to the best possible plan under Case 1. This raises the question of how to size buffers. When the variation in activity duration is large, buffering may be counterproductive, and may not even perform its goal. It may be too low, or too large, increasing costs and duration, without creating the ability to react to external factors. This is an important aspect of buffering.

In Case 4, we attempt to do better by pursuing options for flexibility, i.e., postponement and flexible two-stage designs. The corresponding plan (Figure 3d) gives a duration of 6 to a cost of 11; about 20% increase as compared to the best possible performance under full information (Case 1), but far better than that of the reactive plan (Case 2), and also better than the lean approach (Case 3).

What is more important is that the structure of the proactive and reactive plans differ substantially (the activities to be performed and their sequencing), in that the proactive one "prepares" to adapt real-time information. This is achieved by staging decisions based on information arrival, an essential aspect of planning with options. First-stage decisions are taken in light of uncertainty (standardized to fit both designs before Period 4), and second-stage decisions customized to real-time preferences.

4.2. Utility Evaluation Using a Real Case

We built on the Hospital Building Project in [61] to demonstrate the expected gain if flexibility was implemented into the applied lean project delivery solution. We do not replicate that case but provide a different way of analyzing the results, including decision trees. The case makes use of the true lean master plan developed by pull planning, as described by a lead practitioner involved in that process [61]:

> "*We had enabling work in this project. We did pull planning, but it didn't become a primary driver of the job. In XX hospital project we had to literally move a mountain (700,000CY of earth) before we could start construction. This was considered as an enabling project so it gave the designers ample time to get the project developed so design would not impact our construction schedule. However, our schedule process was as follows: We developed a Master Schedule or what we called a Validated Target Schedule (VTS) at the initial alignment meeting when YY conducted our offsite Business Case validation meeting. Next, we developed a Pull Schedule from the major milestones off the Master schedule with the major trade contractors. Then we refined the schedule as the design developed and conducted weekly work plans with the people or leaders of the teams that actually performed the work. We only tracked PPC, but we did our learning from our weekly analysis of our PPC and discussions stemming from that data at our weekly work plan meetings.*"

Options implemented into the pull plan are hypothesized, based on uncertainties that have, and could have, impacted the project (knowable unknown-unknowns). These are listed by lead practitioners, as follows: change in site location, change in dental equipment, change in surgery suite design, and change in pharmacy pick system design. For our scope, change in dental equipment (type and quantity of chairs) is chosen. This change is driven by uncertainty in demand for dental services in the hospital region and is expected due to market (demography) uncertainty, although the exact type and size of change is difficult to predict. This uncertainty is estimated to be revealed far into the Construction and Prefabrication phase, which takes 413 days, following the Team Selection and Alignment Process phase of 349 days, and the Design phase with 229 days. The last phase, Commission and Inspect, takes 88 days.

We assumed two possible demand outcomes: stable (with an estimate of 10 dental chairs) and increase due to expected demographic changes (up to doubled demand, implying 20 dental chairs). This represents an opportunity. Following the planning process in Section 5, the option "Delay of the decision on the dental equipment type and quantity, until relevant demand information is obtained" was implemented into the lean master plan. This option carries the mutually dependent sub-options: (1) shell option, to prepare the foundation and floor plan to enable late installation of different types and numbers of chairs (increase space, specify easily removed flooring to install equipment support and others); (2) option contract for a commitment from suppliers to reserve capacity for dental equipment up to the increased demand level.

The question to answer for a decision maker is: (i) should the project continue with the current estimate for dental equipment, which is 10, and accept unsatisfied demand in case of increase (deterministic lean approach), or (ii) should it react only if a change occurs, with an update that requires revising multiple project phases with collateral impacts (time, money, and project momentum) on surrounding construction (reactive lean approach)? Or (iii) should the option be implemented into the project plan to enable timely and cost-efficient reaction to demand increase (proactive lean approach)?

Under (assumed) known demand, all decisions are fixed early (call it D). However, when demand turns to be different, this approach is leading to iterations and rework loops in three out of four phases (Team Selection and Alignment, Design, and Construction. See [60] for details on the impacted activities and their cost-duration estimates). In the proactive approach, with an option implemented in the Team Selection and Alignment phase, rework loops are limited to the Design and Construction phases, and the decision process is staged: with first-stage decision D1 before learning the demand, developed to fit both demand scenarios, and second-stage decisions developed to fit the observed demand (denote $D2^{Alt1}$ for stable demand, and $D2^{Alt2}$ for increased demand).

Table 3 shows the impact of demand changes on project performance (costs and durations) for the three solutions: deterministic, reactive, and proactive, respectively. The results are given for the subproject of dental clinic design and for the entire project (the latter in parentheses). For calculations, we assumed that 33 days equal one unit of time, and USD 1 million equals one unit of cost. Observe that when demand is as expected, the deterministic solution outperforms the flexible one. However, this solution performs badly if demand turns out to be different from the expected one: We report over 300% increase in costs and time for the subproject, an increase in duration from 2.25 to 6.95, and increase in costs from 5.6 to 17.3. For the entire project, we note an 11.3% increase in project duration and 7.8% increase in total costs. Whether this is acceptable is subject to a collaborative discussion across stakeholders. Under the proactive strategy, the subproject duration is 2.9 and the cost 7.2, for both demand scenarios. This performance is somewhat lower than the best possible when everything is (assumed) known, but far better than that of the reactive plan.

Table 3. Comparing different planning approaches to handle the uncertainty at hand.

	Planning Solution	Demand Satisfied	Lost Demand	Duration Subproject (Entire Project)	Costs Subproject (Entire Project)
Demand scenario 1	Deterministic	10	0	2.25 (20.8)	5.6 (75)
	Proactive	10	0	2.9 (21.45)	7.2 (76.6)
Demand scenario 2	Deterministic	10	10	2.25 (20.8)	5.6 (75)
	Reactive	20	0	6.95 (25.5)	17.3 (86.7)
	Proactive	20	0	2.9 (21.5)	7.2 (76.6)

To answer the question of which decision to choose, we applied the stochastic decision tree approach and calculated the value of flexibility—the difference between the expected value of the project with and without options. This value was evaluated under two situations: (i) high belief in unchanged/stable demand (common assumption in practice), with probability 0.9; and (ii) equal belief in the two demand scenarios, with probability 0.5 (which practically means limited predictability, and the context of the paper at hand). Without additional information on the future demand, the latter is the correct assumption.

The decision tree under high belief in stable demand is shown by Figure 4, with the rectangular nodes representing decisions and valuation nodes and the circular nodes representing chance (uncertainty) nodes. The decision process moves upward in the decision tree. The performance measures are provided in the decision tree, for both the subproject and the entire project. The expected subproject costs with the option (7.2) minus the expected costs without the option (6.77) suggest that the value of flexibility is negative (higher costs means negative value). This, in order, suggests that the fixed design solution, with all decisions taken early and reaction to a materialized change, should be chosen. This is not unexpected; options and flexibility are less valued under low levels of uncertainty. On the other hand, under high levels of uncertainty (i.e., equal belief in the two demand scenarios), the expected performance of the proactive strategy is substantially better than that of the reactive one (duration of 2.9 vs. 4.6; costs of 7.2 vs. 11.45). This situation is not illustrated by a decision tree. The value of flexibility is positive, suggesting that the decision with options is to be preferred. Expectedly, options for flexibility are more valued under higher levels of uncertainty.

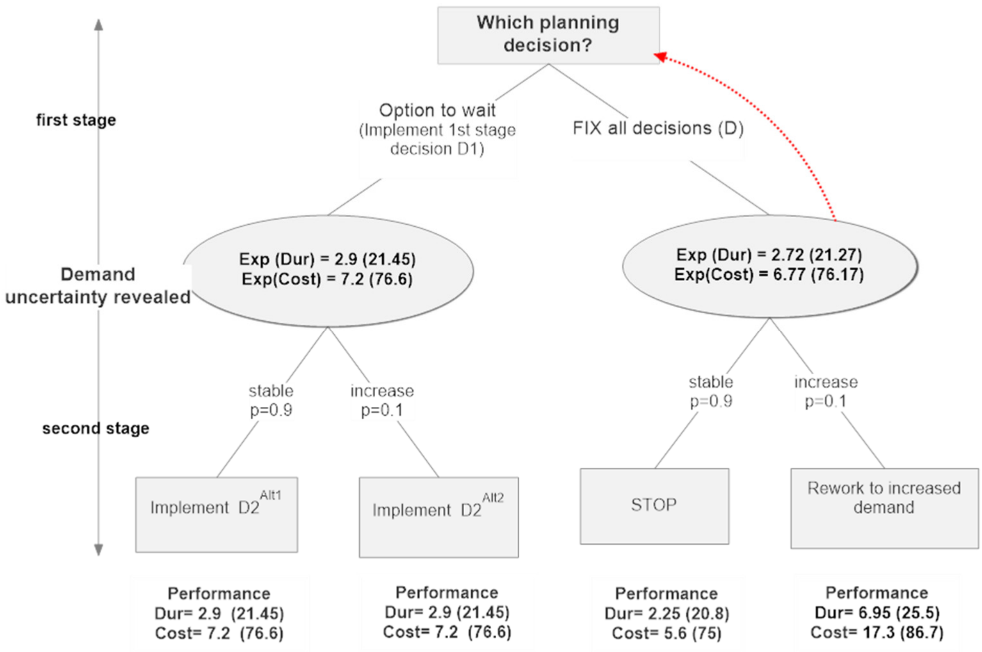

Figure 4. Decision tree with high belief in stable demand (p = 0.9).

In summary, the proactive planning approach with options enables flexibility to achieve cost efficient and timely delivery of demand increase. Typically, reactive approaches are costly in time and money, and they tend to hurt team chemistry and project momentum. Flexibility may be necessary to effectively switch to alternative solutions. However, options usually come with extra costs that may exceed the cost of doing nothing. Quantification is needed before the decision is taken.

5. Contributions and Conclusions

The main result and contribution is the proposed operational system, with options for flexibility implemented into master control schedules within the frame of lean project delivery, along with test results to evaluate the value of planned flexibility, as laid out in Sections 3 and 4. The solution enables the combinative capabilities of lean efficiency through waste reduction and flexibility to pursue objectives and implementation pathways that may change during the course of the project.

This section concludes with insights this research provides to managing complex dynamically changing projects.

(1) The insight the multidisciplinary DSR provides to the management of ETO and construction projects: It is stated that future project management research needs dynamic and agile approaches that are effective responses to real challenges, and that make academic research more relevant to practice [33]. The research presented here demonstrates how to make model-based research more relevant to practice, and more relevant for project management processes associated with learning. Further, we demonstrated the agility and dynamic capabilities of DSR to develop new knowledge for the management of project uncertainty. These capabilities are achieved by learning loops of build-evaluate., until a customized planning solution to a particular field project is achieved ('customized' in the sense of the chosen level of flexibility, aligned with performance measures agreed upon in collaborative front-end phases).

We know that higher levels of flexibility enable improved adaptability, but this comes with additional costs. We also know that lower levels of flexibility may nearly capture the benefits of full flexibility [48]. However, what is the 'right' level of flexibility? An exact answer is difficult to obtain in complex projects. Model-based research has helped to improve understanding on what flexibility is appropriate in different circumstances, but these are difficult to apply in practice. What practitioners can do is to apply DSR to quickly build-evaluate. different levels of flexibility before the decision is taken. The guidelines to follow in this process are provided in Section 3. The methods and tools to apply within these steps may vary according to the means available to a particular field project. For example, we propose uncertainty assessment by the impact of a change in system perspective, disregarding change probabilities [76], but other methods may be more appropriate in a given context.

(2) The insight the proposed planning approach provides to the management of lean projects. We highlight three main aspects of the results: (i) Guidelines professionals can use to customize their lean construction practices to uncertain contexts, consisting of component processes for pull planning, uncertainty assessment by assessing the impact of changes disregarding their probabilities, and incorporating options into the project milestone schedule (described in Section 3). (ii) Guidelines to evaluate quantitatively whether the project with a chosen level of flexibility can be delivered within performance measures agreed upon (described in Section 4). This is also related to project and business case validation. (iii) Guidelines to explore the value of planned flexibility for capturing opportunities resulting from customer-driven changes (as shown by the case in Section 4.2).

The practical relevance and external validity of this research is increased by the wide adoption of LPS® in the AEC industry, and increasingly in ETO projects, such as shipbuilding, as a mechanism to implement lean construction.

Limitations and future research direction: The research is a proof of concept of the proposed operational planning solution, to illustrate the potential gain from the proposed solution. Actual validation in practice—with iterations based on the practitioners' reflections regarding the usability and value of the approach—is not performed within the frame of this paper. This is planned for future research, as proposed in [83].

Author Contributions: The authors bring in their core scientific competencies and fields of research, and equally contributed to conceptualization, methodology, development, and validation. G.B. is the developer of the Last Planner System (LPS), and as a co-founder of both the International Group for Lean Construction and the Lean Construction Institute—USA, he brings in knowledge on implementing lean in project-based production systems. H.V. brings in research in operational risk management, decision making under uncertainty, and stochastic optimization approaches to integrating design and project planning in projects. All authors have read and agreed to the published version of the manuscript.

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