A method to lean product development planning

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Abstract.: This paper describes a systematic method for the creation of the product development project's activity network, which provides at the same time value creation and waste reduction as it was advocated by the lean philosophy. The proposal of a new method is justified due to the low performance of the traditional project management when applied to the development of complex products. The proposed method is composed of four processes: value determination, set-based concurrent engineering (SBCE) prioritization, pull event determination, and value creation activity sequencing. A possible implementation of the method is also introduced using a technique called value function deployment (VFD). The VFD relates the value items (what) to the teams (who) and the pull events (when). The pull events themselves pull the activities (how) that will be performed by the development teams. To ilustrate the use of the method and show the application of the VFD, an example of product development planning is given. Conclusions are that the developed method: 1) fits the product development environment; 2) adheres to the lean principles; 3) avoids the traditional planning deficiencies; and 4) is feasible and produces good results.

Keywords: project management planning, product development, lean philosophy, lean product development.

1. Introduction

The product development system (PDS) is an organizational system that manages both the product portfolio and each individual product development (CHENG, 2003). A high performance PDS, therefore, is capable of consistently articulating market opportunities that match the enterprise's competencies (CHENG, 2003), and executing the Product Development Process (PDP), guaranteeing that progress is made and value is added by creating useful and timely results (DE MEYER et al., 2002; MURMAN et al., 2002).

The PDP itself is a creative, innovative, interdisciplinary, dynamic, highly coupled, massively parallel, iterative, communication based, uncertain, and risky process of intensive planning and activity (NEGELE et al., 1999). Consequently, a wide spectrum of variables can affect its success, and, not surprisingly, overtime, over budget and low quality are commonplaces on PD projects. Indeed, although being largely taught and practiced, the traditional project management has low performance when applied to the development of complex products (BROWNING, 1998; HOWELL; KOSKELA, 2000).

A great exception in this scenario, and benchmark on the automotive industry, is the Toyota Motor Company. Toyota has, consistently, succeeded in its PD projects, presenting productivity four times better then its rivals (KENNEDY, 2003). The reason for this success is credited to the lean philosophy/thinking, of which Toyota is the creator and best practitioner. Unfortunately, unlike Toyota Production System (TPS), that was formalized by Shigeo Shingo and enforced by Taichii Ohno, the Toyota Development System has not been well documented (WARD et al., 1995; SOBEK et al., 1999).

Previous work on lean product development (KENNEDY, 2003; MORGAN; LIKER, 2006; WARD, 2007) focused on understanding and describing Toyota's practices, in order to help companies implement lean systems themselves, where the concerns were rather on the development execution than on the development planning. This work aims to fill this gap, by proposing and validating a systematic way to plan for the lean development of engineering products. The proposed method allows the creation of an activity network, which provides at the same time value creation and waste reduction. One possible implementation of the method is also introduced, using a technique called value function deployment (VFD).

This paper is divided into seven sections. Section 2 justifies the need of a novel planning approach by discussing the weaknesses of traditional project management when dealing with development projects. Section 3 analyzes the lean philosophy requirements for product development planning. In Section 4, the proposed approach, its processes, and the VFD technique are described. Next, in Section 5, an example of the used approach is presented through a what-if analysis of a real project. Section 6 discusses how the method deals with the identified weaknesses of traditional project management while adherent to the lean principles. Finally, Section 7 presents some conclusions and suggestions for future work.

2. Traditional planning weaknesses

The PDP is executed through development projects, where the project management process is fully utilized (HAMILTON, 2002). The project plan is the main result of the planning process, and is the guide to the execution and control (PMI, 2004); acoording to Murman et al. (2002), the plan is the value proposition itself. While the need of good planning is widely recognized as a critical success factor to any project (SUSMAN 1992; BLANCHARD; WOLTER, 1998; HUNGER, 1995; COOPER; CHAPMAN, 1987), traditional planning has low performance when applied to the development of complex products (BROWNING, 1998; HOWELL; KOSKELA, 2000). The identified reasons for this low performance are:

- the need of a single "low-risk" solution – To guarantee the scope, schedule and cost stabilities, traditional planning assumes a low uncertainty level on the scope definition, by choosing a single "low-risk" solution early in the development process in detriment of other viable solutions (KENNEDY, 2003). In reality, there is indeed a high uncertainty due to constant changes (HOWELL; KOSKELA, 2000);
- loss of systemic vision – The product and work are decomposed into smaller and more manageable parts using a "divide and conquer" strategy, causing the loss of the systemic vision (PESSÔA, 2006). Activities to build them are then listed in a "logical sequence", assuming the availability of perfect and opportune information about the other elements (parts, subsystems, etc.) (WILLIAMS, 1999);
- the assumption of simple and sequential dependencies – The development activities are represented by Pert/CPM-like network diagrams, assuming simple and sequential dependencies, and not considering decision points and rework cycles (KENNEDY, 2003). The activities' relationships are neither simple nor sequential; reality is more complex: activities are interdependent and commonly are started before the end of their predecessors;
- the incorporation of a transformation view – The transformation view assumes that translating a plan into action is the simple process of issuing and executing "orders," analogously to an MRP (Manufacturing Resource Planning) (KOSKELA; HOWELL, 2002). Activities' results are "pushed" inside the PDP, creating information and prototype inventories. Alternatives to this view are the flow and value aggregation views. The former advocates the elimination of waste from the process, and the latter works on guaranteeing that the expected value will be delivered (BERTELSEN; KOSKELA, 2002); and
- planning to control and not to execute – The main objective of traditional planning is the control and not the execution (LAUFER; TUCKER, 1987). This detachment implies that the planning role changes from the theoretical initiating and directing of the execution to controlling the operations status, where more importance is given to the activities themselves than to their results (BONNAL et al., 2006). This suits contract management (HOWELL; KOSKELA, 2000), but product development should prioritize the results (KENNEDY, 2003).

3. Lean principle adherence

In the 1950s, Eiji Toyoda, Shigeo Shingo and Taiichi Ohno at Toyota Motor Company, in Japan, developed the Toyota Production System (TPS). The TPS relies on the lean thinking (or philosophy), which is a way to specify value, align the value-added actions, when requested execute these actions without interruption, and improve continuously (WOMACK; JONES, 2003).

In PD, adding customer value can be less a function of doing the right activities (or of not doing the wrong ones) than of getting the right information in the right place at the right time (KENNEDY, 2003). Hence, the focus of lean must not be restricted to activity "liposuction" (waste reduction), but must address the PD process as a system (value creation) (BROWNING et al., 2002). To guarantee the value creation and to create the needed countermeasures against waste, the lean thinking relies on five lean principles (WOMACK; JONES, 2003):

- Specify value: The value, as defined by the final client, is the basis of lean thinking. In a program or project, the value is the raison d'être of the project team, which means they must understand all the required product/service characteristics regarding the value that all stakeholders of the program expect to receive during the product life cycle (MURMAN et al., 2002; MASCITELLI, 2002; KENNEDY, 2003);
- Identify the value stream: The value stream is a theoretical and ideal sequence of exclusively value-added tasks (MASCITELLI 2002), where a value-added activity transforms the deliverables of the project in such a way that the customer recognizes the transformation and is willing to pay for it. Consequently, the project plan must be simple, highlighting key dates and responsibilities and defining optimized information flows (what, when, sender, receiver and media),

in order to prevent excessive data traffic and promote efficient communication (PESSÔA et al. 2006);

- guarantee the flow: Every development value flow obstacle (functional departments, executive gate meetings, fire fighting, changing requirements and management interference) must be eliminated (MASCITELLI, 2002). The Set-Based Concurrent Engineering (SBCE) is a powerful technique to guarantee the flow, avoiding risk through redundancy and robustness, and allowing knowledge capture (WARD et al., 1995; SOBEK et al., 1999; KENNEDY, 2003). By the use of SBCE, the development team does not establish an early system level design, but instead defines sets of possibilities for each subsystem, many of which are carried far into the design process. These sets consider all functional and manufacturing perspectives, building redundancy to risk while maintaining design flexibility. The final system design is developed through systematic combining and narrowing of these sets, when alternatives are eliminated according to the growth of knowledge and confidence. The discarded alternatives are themselves considered learn opportunities;
- pull the value: Instead off pushing scheduled activities, which themselves push information and materials through the development process, pull events must be defined. Differently from tall gates, where information batches are created, pull events guarantee the value flow, make quality problems visible and create knowledge (PESSÔA, 2006); and
- seek perfection: The continuous improvement of the development process is achieved by the capability of the process and effective knowledge management. Through the SBCE Toyota performs extensive prototyping at the subsystem level while applying tremendous rigor to how it captures learning: it studies both what works and what does not work. This knowledge is systemically documented and disseminated through trade curves, which everyone can access and is expected to use, including management (KENNEDY, 2003; WARD, 2007).

4. The proposed method

The method described in this section applies the lean principles, based on value creation and waste reduction, to derive a project activity network that is based on a sequenced set of confirmation events. These events pull only the necessary and sufficient information and materials from the product development team. The proposed method has four processes : value determination, SBCE prioritization, pull event determination, and value creation activity sequencing. Each process will be further detailed.

Its application is on the development of engineering products, where the applicability criteria is that the development results include physical (hardware) and sufficiently complex subsystems that must be developed by multidisciplinary teams. Since it can be implemented

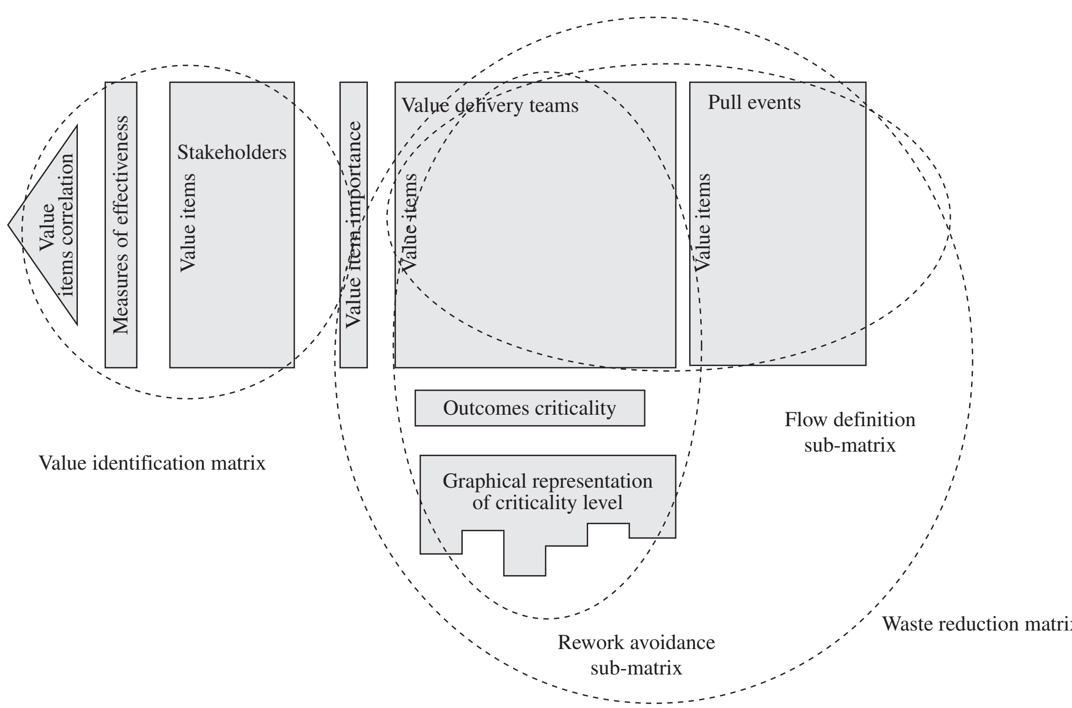


Figure 1. The value function deployment matrices.

using different tools and techniques, this work also introduces a quality function deployment (QFD) adaptation technique called Value Function Deployment (VFD). The VFD is composed of two interconnected matrices, the value identification matrix and the waste reduction matrix (Figure 1). The former captures, prioritizes and shows the correlation between all the value items expected by the project's stakeholders. The latter deploys the value items to the value delivery teams, calculating their criticality (rework avoidance sub-matrix), and defines the events that will pull this value from the teams (flow definition sub-matrix). The example presented in Section 5 describes the VFD's use.

4.1. Value determination

This process guarantees the value specification principle by: avoiding preconceived or any other solution that does not match the expected value, keeping the value as the basis to planning, and using and generating historical information that contributes to continuous improvement. The value determination is divided into five steps (Figure 2 maps these steps on the VFD matrices):

- determine the stakeholders –Stakeholders have to be considered regardless of whether they are inside or outside of the development company, or if they contribute directly or indirectly to the development (which is the case of regulatory agencies);
- analyze the value items – This step includes understanding the stakeholders' needs and breaking them down into value items. The value items remove the ambiguity from the value set, where the items can be addressed to the teams' deliverables and the progress on effectively delivering them measured. For example, a need presented as "be safe" can be broken down into items corresponding to the homologation tests defined by the product's regulatory agency;
- prioritize the value items – Each considered stakeholder has particular needs, thus rates the importance of the value items differently. The value items prioritization takes into account the combination of these ratings;
- define measures of effectiveness (MoE) – At least one measure of effectiveness must be defined for each value item. These measures allow the verification that the items were effectively incorporated into the project's results; and
- identify conflicting value items – Conflicting value items are items that cannot be optimally delivered simultaneously (like having the fastest car and the least fuel consumption car at the same time), if using the current company knowledge and capacity. The conflicting value items direct the creation of trade-off curves that, besides aiding the development team, are part of the company's knowledge assets. By challenging and improving the trade-off curves, a company becomes more competitive.

4.2. Set-based concurrent engineering (SBCE) prioritization

The development of multiple alternatives prevents the early abandonment of promising solutions while giving room to the coexistence with preconceived and advocated alternatives.

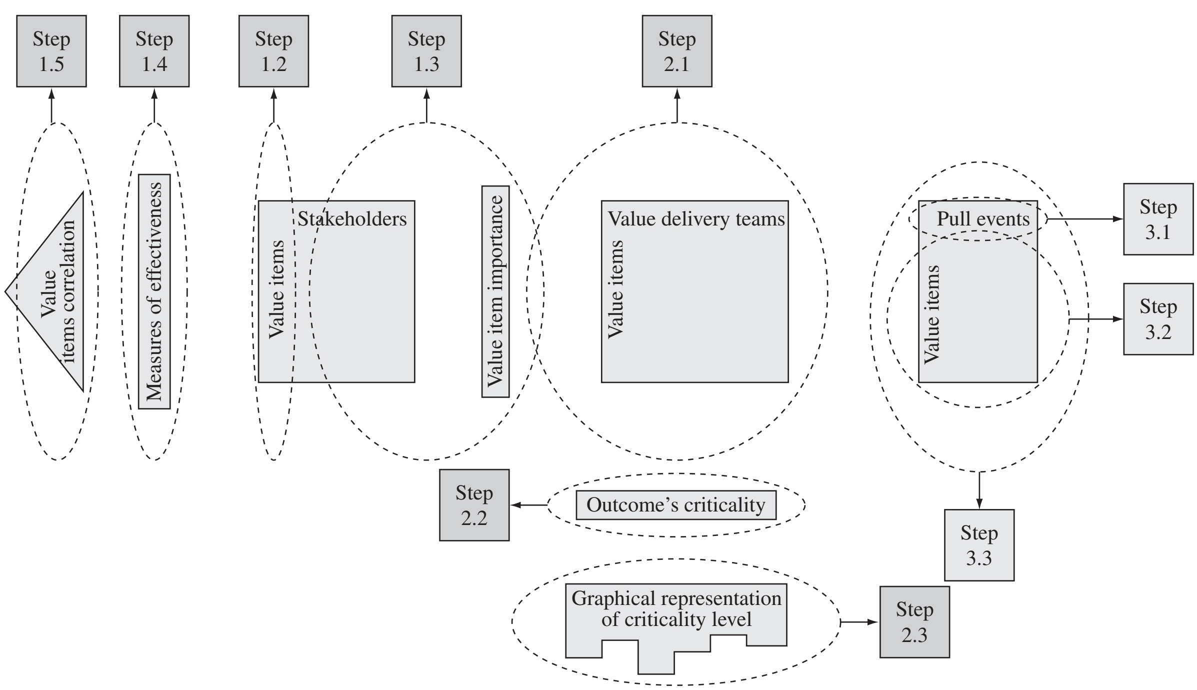


Figure 2. The method's processes and the VFD.

The SBCE helps to guarantee the flow while reducing rework cycles: if one alternative on the set is proven to be inadequate, the others can still be used, and no additional work is necessary. This process determines the most critical product modules or organizational processes that will be developed through a set of alternatives, and is divided into three steps (Figure 2 maps these steps on the VFD matrices):

- define the value delivery teams – This step determines which value teams are responsible for the delivery of each value item. These teams are either related to the product subsystems themselves or to organizational processes (such as marketing, quality, production, etc.);
- calculate the criticality of each team's results – The criticality of the results, which are in charge of a team, is directly proportional to: 1) the amount and importance of value to be incorporated in these results; and 2) the perceived risk to successfully deliver the expected value subset. The more valuable and the more risky, the more critical are the results; and
- define the priority to parallel development – The teams whose results will be developed through a set of alternatives will be chosen considering the restrictions imposed on the development project and the previously calculated criticality. The definition of the number of alternatives and the characteristics of each of the alternatives is outside of the proposed method's scope.

4.3. Pull event determination

No process along the value flow should produce an item, part, service or information without direct request from the afterward processes. The pull events are the backbone of the value flow and are important moments to knowledge capture; by pulling the value delivery, they allow the planning to execution. Every pull event is associated with physical progress evidences (i.e., models, prototypes, start of production, etc.). The pull event determination process is divided into three steps (Figure 2 maps the steps on the VFD matrices):

- define preliminary pull events – To define a sequence of preliminary pull events, the development team can use the enterprise's standard process (if there is one), reuse historical information from previous projects, or consider best practices from the industry;
- relate the pull events and the value items – A pull event scope is defined by the set of value items it will check and how they will be checked (i.e. analysis, subsystem tests, integrated tests, etc.). A pull event must be related to at least one value item, and each value item must be checked by at least one pull event; and
- refine the pull event set – The preliminary pull event set is refined until it meets the following criteria: 1) it must be capable of verifying the progress on the effective value incorporation and delivering during the project execution; 2) it must represent the value flow in order to guarantee the information pull, and not push; and 3) it must show the elimination of the risks that led to the development of multiple alternatives, allowing the combination and the reduction of the number of alternatives during the SBCE.

4.4. Value creation activities sequencing

The activities are pulled from each development team by the pull events. These activities represent the necessary and sufficient work to deliver the results needed to perform the pull event. The value creation activities sequencing process is divided into three steps (Figure 3):

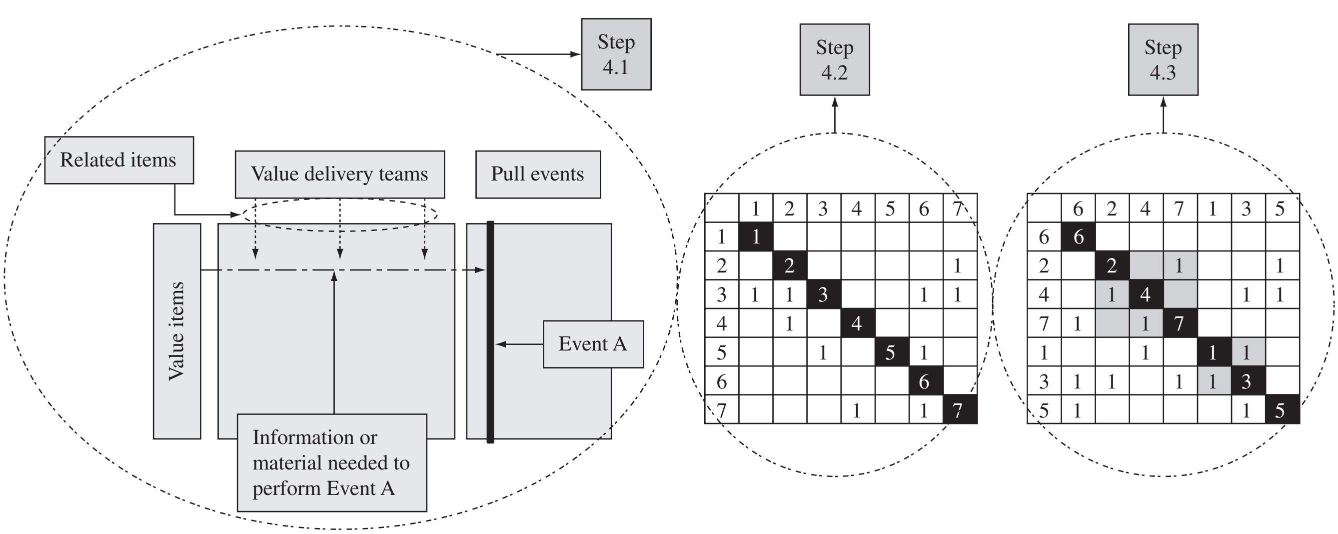


Figure 3. Value creation activities sequencing process steps.

- determine pulled activities – When a value item is on the scope of a pull event, all the teams which help deliver this item have to provide the information and/or materials needed for the event. For example, if some functional value is going to be analyzed during an event, the teams should provide their designs showing how they incorporated the expected value; on the other hand, if the item will be tested, the teams should provide their prototypes for testing;
- identify dependency between activities – A dependency between activities exists whenever one needs the results (information and/or materials) from the other. In this work, these dependencies are represented through an activity-based Design Structure Matrix (DSM). An activity-based DSM is a square matrix with the same values (activities) on both rows and columns; dependencies are shown whenever results from an activity in a column are needed to perform an activity on a line. For a formal introduction to DSM, refer to Steward (1981) and Yassine (2004); and
- define the activity network – According to the identified dependencies, the sequence is defined and a network can be created. To reduce the possible impact of rework cycles, this work sequences activities by partitioning the DSM. The partitioning algorithm (YASSINE, 2004) is employed to reorder the activities and lower triangularize the DSM.

5. Practical example

As an example of development planning, the data collected from a finished and successful project was used, which produced a stall recovery system to be used during flight tests. The original development was planned to take place from May 2001 to January 2002, but issues delayed the end of the project to June 2002. The study was made based on the development's original documentation (contract, specifications, project management plan, schedule, and homologation plan). The company also supported the study by assigning an engineer who worked on the actual development, and letting other engineers participate on request. In sequence, each of the method's processes is explained on the context of the example; to facilitate the crosscheck with the processes' steps, described in Section 4, the reference to each step is highlighted in bold.

5.1. Value determination

During the **stakeholders' identification** all stakeholders who directly interact with the product and the life cycle processes were considered. The needs from these stakeholders were identified from either analyzing the original project documentation or interviewing representing of the stakeholder's categories. Through the **value items analysis**, these needs were further translated into value items. To prioritize the value items, their importance was calculated as "*item_importance* = Σ *stakeholder_relevance* * *interest_to_stakeholder*", where: the *stakeholder_relevance* ranged from 9, 3, and 1, if the stakeholder was considered as primary, secondary or tertiary, respectively; and the *interest_to_stakeholder* ranged from 9, 3, 1, and 0, on the case of high, medium, low, and none, respectively. Table 1 shows the considered

Table 1. Value importance to the stakeholders.

Expected value	Value items	Client	Enterprise - owners	Enterprise - business unit	Enterprise - quality department	Enterprise - industrial engineering	Enterprise - production	Enterprise - homologation	Enterprise -commercial department	Enterprise - logistics	Suppliers - pieces and parts	Suppliers - labs and testing	Importance
		Pri	Pri	Pri	Sec	Sec	Pri	Sec	Sec	Sec	Ter	Ter	
1 Realign the aircraft	1.1 Trigger the system	a	m	a	m	m	m	m	m	m	m	b	360
	1.2 Return to normal flight attitude	a	m	a	m	m	m	m	m	m	m	b	360
	1.3 Eliminate the system's aerodynamic effects on the aircraft	m	b	b	b	b	b	b	b	b	b	b	108
	1.4 Eliminate the system's electric effects on the aircraft	b	b	b	b	b	b	b	b	b	b	b	90

stakeholders and a value items subset, where the linking between the "client" and the value item "trigger the system," contributing with "81" (primary * high = 9 * 9) to the total importance of this item (360).

The measures of effectiveness were defined in order to help the verifications during the product homologation, and according to the project homologation plan. For example, the measure of effectiveness to the value item "return to the normal flight attitude" was "return the aircrafts' angle of attack (AoA) to M +/- D degrees in less than T seconds." Finally, one of the identified conflicting value items was between the trying to have a robust and fail proof product, while aiming to a minimum mass.

5.2. Set-based concurrent engineering (SBCE) prioritization

The considered value delivery teams were: the teams related to the product subsystems, according to the original project documentation; and the already identified stakeholders who somehow contributed delivering some value (Table 2). The team effective contribution of delivering a value item defined the relation among them (high = 9; medium = 3; low = 1; and none = 0). The team's results criticality was calculated through the following steps: 1) the total importance of each value item was proportionally distributed to the teams, weighted by their effective contribution; 2) the total value (TV) was the sum of all weighted contributions. The pilot control panel team, for instance, summed 435; 3) the perceived risk (PR) was determined through interviews with the teams, when they listed the perceived main risks and their individual impact and probability of occurrence; and 4) the final criticality to each team's deliverables was calculated as TV*PR/100.

The priority to parallel development can be verified through the analysis of the final criticality values presented in Table 2. The most critical subsystem was the parachute launcher, which was indeed the subsystem that caused more rework and consequent delays in the project. One interesting outcome of the method was the ranking of the business unit's results as the fourth most critical. This shows the importance of the Business Unit during the contract negotiation and the consequences of a badly negotiated contract.

5.3. Pull events determination

Twelve pull events were preliminarily defined based on the original project homologation plan, and a "proposal" event was added at the beginning of the project (Figure 4). Once two or more events have related activities occurring in parallel, they cannot be characterized as phase gates.

Table 2. Calculation of the team's results criticality.

Value item	Importance	PCP - pilot control panel	TEP - test engineer panel	PCH - parachute	PCL - parachute launcher	TCJ - trailing cone jettinson	PCJ - parachute jettinson	LCK - lock unlock system	TEQ - test equipment	Client	EOW - enterprise's owners	ECD - enteprise's commercial department	EBU - enterprise's business unit	EQD - enterprise's industrial engineering	EIE - enterprise's industrial engineering	EProd - enterprise's production	EHom - enterprise's homologation	ESD - enterprise's suppliers department	ELog - enterprise's logistics	EAdm - enterprise's administrative	SPP - suppliers of pieces and parts	SLT - suppliers of labs and test facilities
1.1 Trigger the system	360	a	m	m	a				m					b			a					
		87.6	29.2	29.2	87.6				29.2					9.7			87.6					
1.2 Return to normal flight attitude	360			a										b			m				m	
				202.5										22.5			67.5				67.5	
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Total value (TV)		435	500	832	726	651	538	429	204	188	29	204	707	541	205	455	274	43	119	131	156	51
Perceived risk (PR)		13	13	15	31	17	17	20	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Final (TV*PR/100)		58	67	125	224	108	90	86	27	25	4	27	94	72	27	61	37	6	16	17	21	7

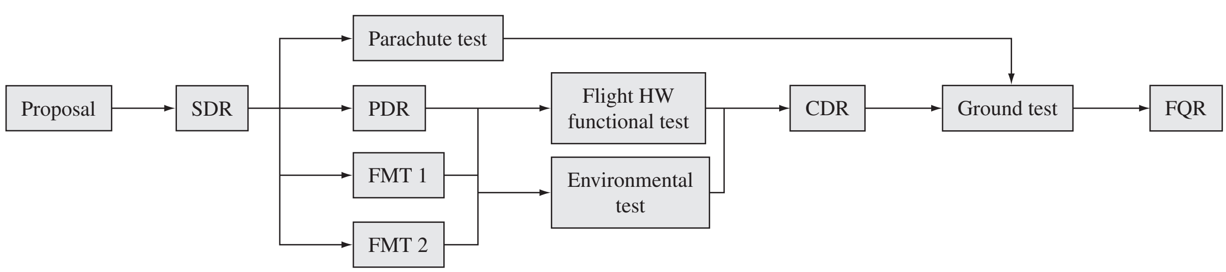
The pull events were related to the value items according to the verifications that would be executed: analysis (A), inspection (I), calculus/simulation (C), demonstration (D), and test (T). Table 3 shows how the "realign the aircraft" items were related to the defined pull events. During the refining of the pull event set, no preliminary event was excluded or added, but its scope was adjusted in order to more frequently check the items considered more important to the stakeholders.

5.4. Value creation activities sequencing

To guarantee the pull events' success, the necessary and sufficient information and materials are pulled from the development teams. The pulled activities are themselves the activities that will be performed by the teams to provide these needed deliverables. Table 4 presents the subset of the value items that are related to the Parachute Launcher (PCL) development team, and how they were included in the scope of the Proposal pull event (in parenthesis are presented the development activities according to Table 5). Since this is the first development event, the only verification type used was analysis.

Table 5 lists the correspondent PCL development team activities pulled by the Proposal event. Whenever the method application suggested the use of concurrent engineering, the other participant teams are cited (when other teams are related to the same value item, the needed deliverables are pulled from all of them simultaneously). In the case of the development of multiple alternatives, the activities will be repeated for each alternative.

The activities' dependencies were identified and plotted on an activity-based DSM. Figure 5 presents a partial view of the partitioned DSM representing the System Design



Event	Objective
Proposal	To have a feasible contract proposal approved
System design review (SDR)	To have the product systemic conception
Preliminary design review (PDR	To have the subsystems' preliminary engineering designs
Functional model test 1.1 (FMT 1.1)	To approve the riser cutter functional model
Functional model test 1.2 (FMT 1.2)	To approve the trailing cone cutter functional model
Functional model test 1.3 (FMT 1.3)	To approve the riser lock functional model
Functional model test 2 (FMT 2)	To approve the mortar functional model
Parachute test (PT)	To approve the parachute functional model
Flight hardware functional test (FHFT)	To approve the pilot and flight engineer panels functional model
Environmental test (ET)	To approve the environmental model of the integrated system
Critical design review (CDR)	To have the detailed design approved
Ground test (GT)	To approve the system operationally
Final qualification review (FQR)	To have the system qualified by the client

Figure 4. Pull events.

Table 3. Example of pull event's scope.

Value	Poposal	SDR	PDR	EMF1.1	EMF1.2	EMF1.3	EMF2	PT	FHFT	ET	CDR	GT	FQR
1.1 Trigger the system		A	T		T		T			T	A	T	A
1.2 Return to normal flight attitude	A	A	A			T		T			A	D	A
1.3 Eliminate the system's aerodynamic effects on the aircraft		A	A	T						T	A	T	A
1.4 Eliminate the system's electric effects on the aircraft		A	A						D	T	A	T	A

Activity		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Client - to give the list of all changed requirements	1		1			Block 1													
Quality - estimate the capacity to fulfill the requirements (and assess the risk)	2	1																	
UN - prepare the technical specification of the system	3				1			Block 2											
UN - prepare the technical specification of the subsystems	4			1															
Quality - estimate the reuse rate of parts, processess and techniques	5			1	1											Block 3			
UN - plan the development activities	6							1	1	1	1			1	1		1	1	1
UN - determinate the manufacturing needs	7					1	1					1	1						
Quality - plan the homologation activities	8						1			1	1					1	1		
Quality - plan the quality activities	9						1		1		1					1	1		
Quality - commit with the projects schedule and budget	10						1		1	1									
Ind. eng. - support the architecture definition, giving industrial capacity data	11							1						1	1				
Ind. eng. - inform the estimated process reuse	12							1											
Ind. eng. - commit with the project's schedule and budget	13						1												
Production - commit with the project's schedule and budget	14						1												
Tests - estimate the capacity to perform the planned tests	15								1	1									
Tests - commit with the project's schedule and budget	16						1		1	1						1			
Suppliers - commit with the project's schedule and budget	17						1												
Logistics - commit with the project's schedule and budget	18						1												

Figure 5. Partial CDR DSM partitioned.

Table 4. The PCL related value items and the scope of the proposal and the CDR pull events.

Value	Value item	PCL	Proposal
1 Realign aircraft	1.1 Trigger the system	a	
2 Safe and reliable operation	2.2 Have on the ground detection of system unavaibility	a	A (1.1)
	2.2 Work when required (reliability)	a	A (1.2)
	2.3 To not work when not required (safety)	b	
	2.6 Useful life as...	b	A (1.3)
3 Work on aircrafts A and B	3.1 Mass no bigger than X	a	A (1.4)
	3.2 Interface mechanically with aircrafts A and B	a	A (1.5)
	3.3 Interface electrically with aircrafts A and B	b	A (1.6)
	3.5 Operate under the defined environmental conditions	a	A (1.7)
4 Quick and easy maintenance	4.1 Post deploy repair < X	a	A (1.8)
	4.2 Corrective maintenance time below T sec	a	
	4.3 Support Z years in stock	a	A (1.9)
	4.4 Must have technical documentation	m	
	4.5 Have traceability of the produced units	m	
5 The project must be viable	5.4 Comply with legal requirementes	m	
	5.5 Stay within the budget	m	
	5.6 Stay within the deadline	a	
	5.7 Comply with the enterprise's rules	b	
7 Easy to manufacture and test	7.1 Adhere to the design for manufacturing and assembly guidelines	a	
	7.2 Have high rate of reuse of parts, processes and technologies	m	
	7.3 Have complete and concise product, process and tests documentations	m	
	7.4 Have defined product and process acceptance criteria	a	
	7.6 Have more than one supplier to each procured item or raw material	m	

Table 5. Activities pulled from the PCL team.

Proposal
(1.1) Determine alternatives "for the on the ground detection unavailability system" (TCJ, PCJ, TEQ). (1.2) Include the PCL data in the system reliability estimate. (1.3)) Include the PCL data in the useful life estimate. (1.4)) Include the PCL data to the mortar mass estimate (PCH, TCJ, PCJ, LCK). (1.5) Define the preliminary PCL mechanical interfaces. (1.6) Define the preliminary PCL electrical interfaces. (1.7) Estimate the PCL environmental condition limits (PCH, TCJ, PCJ, LCK). (1.8) Estimate the time to post deploy repair. (1.9) Estimate maximum time to keep the system in stock.

Review. The subset shows the activities pulled from the development teams that are not involved in the creation of the product's subsystems, where the dependencies between the activities are represented with "1," and the columns' names are suppressed keeping the reference through their sequence number. After partitioning the DSM, the ordered sequence presents three blocks of interdependent activities: 1) the changing requirements block; 2) the technical specification block; and 3) the planning and commitment block. The activity network is created through the dependencies showed on the partitioned DSM.

6. Evaluation of the method

The method was evaluated according to its adherence to the lean principles described in Section 3, and to its avoidance of the traditional project planning weaknesses listed in Section 2. The way the method deals with these issues is listed as follows (Table 6):

- specify value (lean principle 1) – the method's "Value Determination" process identifies the value expected from all the stakeholders, and helps the balancing of this value through the identification of conflicting value items that can be further addressed by trade-off curves;
- identify the value stream (lean principle 2) – the value stream is the best sequence for value creation during the project. The proposed method identifies the value stream: 1) the pull events pull only the required information and materials from the value delivery teams; 2) the activity sequencing orders the flow; and 3) through the method, the value items are kept central to defining the teams' work and the scope of the events;
- guarantee the flow (lean principle 3) – the proposed method fulfills this principle: 1) the pulled activities are synchronized in order to reduce the rework cycles; 2) the SBCE reduces the rework cycles; and

Table 6. The method coverage on the identified issues.

		Value determination	SBCE prioritization	Pull events determination	Value creation activities quencing
Lean principles	Specify value	x			
	Identify the value stream			x	x
	Guarantee the flow		x		x
	Pull the value			x	
	Seek perfection	x	x	x	x
Issues on traditional planning	Early solution freeze		x		
	Planning to control and not execution	x		x	x
	The transformation view			x	x
	Systemic vision loss	x		x	x

Table 7. Lean principles applied to development planning.

Step	Original Planning	With the Method	Impact
Value determination	Only client's needs related to the final product were considered.	All the stakeholders' needs related to the final product and the life cycle processes were considered.	Create value
SBCE prioritization	Only one solution alternative mainly describes in the contract.	Many alternatives on the parachute launching subsystem (critical to SBCE) would reduce the rework that actually happened.	Reduce waste
Pull events determination	Homologation and test activities were superficially defined.	The test and homologation events were best sequenced and scoped.	Create value Reduce waste
Value creation activities sequencing	The plan was focused on activities based on the standard process.	The plan was focused on the value and based on the value flow.	Create value Reduce waste

3) the pull events prevent the early production of information and material, which are themselves another important rework source, consequently breaking the flow;

- pull the value (lean principle 4) – the proposed method pulls the value: 1) during planning, each pull event pulls from the related teams only the necessary and sufficient activities to accomplish them, avoiding early work; and 2) the created activity network promotes a true pulled system. A pulled flow is created instead of a pushed one, which is the result of traditional schedules;
- seek perfection (lean principle 5) – the seeking of perfection is helped through the generation and use of historical information during the execution of the method's processes;
- the need of a single "low-risk" solution (weakness 1) – The use of SBCE in the "SBCE Prioritization" process solves this issue, allowing several alternatives to coexist even in advanced development phases, according to the strategy defined by the team;
- loss of systemic vision (weakness 2) – by having the value items as its core, the method gives a clear picture of how each team contributes to the whole. Even during the execution, since the pull events' scope is also based on the value items, the systemic vision is not lost;
- the assumption of simple and sequential dependencies (weakness 3) – the dependencies representation through an activity-based DSM captures all the complexity of these relationships, and helps to deal with them through the use of concurrent engineering;
- the incorporation of a transformation view (weakness 4) – the proposed method incorporates the value aggregation view, by sequencing the value creation, and the flow view, by creating a net of pull events; and
- planning to control and not to execute (weakness 5) – all the planning focuses on effective value creation, and the pulled activities are the very ones that create the expected value.

Regarding the example presented in Section 5, the use of the method presented superior results from the original project development plan (Table 7). The method was also applied during two other pilot projects where the companies highlighted the following benefits: 1) helps to avoid the premature convergence and commitment to a particular solution; 2) reduces the empiricism from the reviews; 3) helps to efficiently perform concurrent engineering; 4) defines activities that very much resemble what really happens during the execution; 5) captures the real needs from the client and helps to "create the right product"; and 6) can be used both during typical developments and during innovative developments (that normally do not fit in the companies' standard processes). Besides these strengths, the companies also listed some weaknesses: 1) the difficulty of gathering and balancing the value expected by all the stakeholders; 2) the difficulty of defining a good pull event set; and 3) the complexity of the method, particularly the use of the DSM.

7. Conclusions

The method presented in this paper provides an alternate planning approach for complex engineering product development that systematically implements some of the lean product development principles and practices. Previous works on lean product development provided rather principles and frameworks, than a systematic method, and were mainly focused on the development execution instead of on the development planning. Conclusions are that the developed method: 1) fits the product development environment; 2) adheres to the lean principles; 3) avoids the traditional planning deficiencies; and 4) is feasible and produces good results. This work's main contributions are:

- the justification, proposal and demonstration of a planning method applicable to engineering products development projects, which is based on the lean principles and can either be used on typical or innovative developments;
- the proposal and demonstration of the value breakdown structure (VBS), as a way to represent the value breakdown as value items and the respective measures of effectiveness;
- the proposal and demonstration of the value function deployment (VFD), which was created based on adaptations of commonly used tools and techniques. The VFD helps the creation of the value proposition, and relates the value items (what) to the teams (who) and the pull events (when); the pull events themselves pull the activities (how) that will be performed by the development teams. The VFD also contributes to effective concurrent engineering, by identifying the value delivery teams that contribute to deliver the same value item; and
- the proposed method can be summarized in four steps: 1) the value expected by the stakeholders is detailed, resulting in the definition of the VBS and on the identification of conflicting value items; 2) a priority is defined to apply the development of multiple alternatives, based on the criticality of the results in charge of the development teams; 3) a set of pull events is defined, in order to guarantee the value delivery, the elimination of alternatives during the SBCE, the pull development, and the organizational learning; and 4) the development activities are pulled and sequenced, such that an activity network with reduced expected rework cycles is produced.

By studying an example of the method's application and the VFD's use, useful insight was gained about its capacity to adhere to the lean principles while avoid the traditional planning weaknesses. However, these findings cannot be generalized before the method is applied in more projects, and until the end of the planning processes. Some suggestions to future work are:

- the method could be extended to encompass all the planning process group processes, particularly the resources and cost issues, in order to define the activity duration and consequently create the project schedule;
- quantitative methods could be used to help the definition pull events and the balancing of their scope (which verification type should be used based on the cost constraints). The question is how many events should be related to a particular value item in order to reduce the risk of failing to deliver it, restricted by the cost of the verification and considering the item's importance; and
- scale the method to programs and even the development of product families. The great challenge in this case is the increasing size and complexity of the events' DSM.

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