Review of Value and Lean in Complex Product Development

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ABSTRACT

Approaches are being developed to improve complex product development from the perspective of value generation. However, the ideas and their relationships are still not fully articulated. We provide a structured literature review, with a primary but not exclusive focus on value ideas relating to lean in complex system product development. A framework organizes the concepts, methods, and their relationships. It clarifies the value delivery mechanism and could help to understand and thus improve value systems. Areas deserving further research attention are identified.

Keywords: value; lean; complex system product development; literature review

1. Introduction

Complex system product development processes (PDP) create value through design [Vosgien et al. 2011] and can thus have a critical impact on a company's success [Browning and Ramasesh, 2007]. This article draws on literature review to develop a framework that explains how the PDP generates value, and how this may be enhanced through lean in product development (LPD). The questions addressed are:

1) What is the current understanding of complex system value in LPD and related fields?

2) What value-oriented principles, practices and approaches have been proposed to improve the PDP, and how do they align against different aspects of value delivery?

3) What are the shortcomings of value ideas and methods that deserve further research attention?

The review considers research that develops the value concept or presents a methodology for improving PDP capacity to generate value. To align with the focus of most LPD literature it centers on, but is not strictly limited to, complex system product development (PD) in which value is determined by disparate stakeholder concerns, requirements and preferences, and is generated by the interactions between many activities and individuals involved in PD. We abridge Browning and Honour [2008] in defining a stakeholder as "any individual or group with a vested interest in a system”. The ultimate value delivered from PD to one very important class of stakeholder, the system users, is the enablement provided by a product, system or service. In this article we focus more narrowly on the value of the recipe generated by the PDP, i.e. information for producing complex products [Reinertsen, 1999]. The analysis focuses on value thinking as adopted from lean PD and relevant Systems Engineering (SE) literature.

The review includes publications since the 1990s. We considered journals, conference proceedings, and books, along with workshop proceedings, presentation materials, and content from the MIT and UK Lean Aerospace Initiative websites. Bibliographies from items identified through keyword search were consulted, and reviewers of the manuscript suggested additional sources. The search yielded several hundred publications. The abstracts were reviewed to select those in scope.

2. Background

2.1. Definitions of PD value in the literature

Value integrates development of products, services and business [Randmaa et al. 2011]. It is multi-dimensional, comprising quantitative and qualitative aspects that may be difficult to attribute to certain features of a product, system or item [Gudem et al. 2011]. Perceptions of value incorporate emotional as well as functional and utilitarian judgments [Zhao et al. 2008].

There are many definitions and perspectives on value. For instance, Rouse and Boff [2001] define value of R&D organizations in terms of three dimensions: quality of outputs, productivity, and innovation capacity. Value in the context of project management (PM) has been discussed in terms of efficiency of projects, benefits to customers, benefits to the organization, and preparation for the future ([DeCotiis and Dyer, 1979]; [Pinto and Slevin, 1988]). In lean production, value is defined as a specific product that meets customer needs at a specific price at a specific time [Womack and Jones, 1996]. In Lean System Engineering, value has been defined as a flawless product delivered at minimum cost, in the shortest possible time, to satisfy all stakeholders during the product lifecycle [Oppenheim, 2011]. Value of a PD process is commonly associated with capacity to generate knowledge or information. For example, Walton defines value as the right information product delivered at the right time to the downstream customers [Walton, 1999]. Oppenheim suggests that value is associated with (1) product quality and (2) reduction in cost and schedule achieved by waste reduction [Oppenheim, 2004].

Many of the value aspects indicated above are difficult to measure. Traditionally though, LPD has considered or required value to be universal, coherent and quantitative [Gudem et al. 2011]. The value-driven design movement similarly promotes the development of consistent value models that compute the value of a system from its attributes and its subsystem attributes [Collopy and Hollingsworth 2011]. From the quantitative perspective PD value has been defined in terms such as functionality divided by cost of a product [Park, 1998], amount by which risk is reduced per resource expended [Browning et al. 2002], and change in economic value of the work product [Reinertsen, 2009].

The definitions can appear inconsistent, because each focuses on only a few dimensions of the superset discussed (Table 1). This is because the definitions have different purposes and because multiple perspectives on PDP value are possible. It is generally agreed that value has many forms, and thus Allee [2008] suggests that a company's success depends on its efficiency in converting value from one form into another.

Table 1 Some PD value definitions in the literature

Focus	**Definition of value**
Value in Lean System Engineering [Oppenheim et al. 2011]	Complex system value is associated with satisfying all stakeholders, which implies a flawless product/ mission, delivered with minimum cost, shortest possible schedule.
Earned Value [PMI, 1996]	Value is defined as the sum of financial values of intermediate project deliverables. Used as a measure of project performance, comparing the value of work planned with the value delivered.
Project Value [Zhai, 2009]	The explicit and implicit functions of the project, which can satisfy all needs of stakeholders, such as time, cost, quality, commercial interests, social benefits, and technological development.
Value in PD [Walton, 1999]	'The right information product delivered at the right time to downstream process/customers where it is quantified by form, fit, function and timeliness'
Value of product or service [Slack, 1999]	'A measurement of the worth of a specific product or service by a customer and is a function of 1) the product usefulness in satisfying a customer need 2) relative importance of the need being satisfied and 3) exchange cost to customer'
Value of product or service [Gale, 1994]	'Market perceived quality adjusted for the relative price of the product/service, where market perceived value is customer's opinion of product/service relative to the competitive market'
Value according to value engineering [Park, 1998]	Value is provided by product, service or system functions that incur a given cost to provide. Cost may be reduced through a structured process considering alternative methods to provide those functions.
Value to organizational stakeholder [Mills et al.	Value is associated with 'the trade-offs between what each stakeholder gets and what they have to give up, in terms of benefits obtained and sacrifices made, and the resources consumed'

2006]	
Value to employee [Donovan et al. 1998]	'A function of both compensation the employee receives from the company as well as job quality'
Value to shareholder [Slack, 1999]	'The potential for future sales and profits of the realized product'

2.2. Lean Product Development (LPD)

Since the 1990s, there has been a significant increase in publications on LPD [Baines et al. 2006]. In overview, it may be described as an approach to maximizing value through an emphasis on 'eliminating' waste. There is a focus on achieving smooth flow of information and addressing the root causes of non-value-added activity such as rework and waiting for information [Oppenheim et al. 2011], achieved through a culture of continuous improvement at all levels of an organization [Liker and Morgan, 2006].

A set of tools and practices have been developed or adopted by LPD, e.g., A3 problem solving and set-based concurrent engineering [Ward et al. 1995]. It is considered that the practices fit together as a system and must be implemented in combination to be fully effective. A lean approach to PD is thought to lead to high-level improvements such as delivering the right product, achieving process efficiency, and achieving effective lifecycle integration [McManus, 2005] – thus enhancing many of the aspects of value outlined in §2.1. Efforts are also being made to integrate lean wisdom, principles, practices and tools into SE practice, with the objective of enhancing delivery of value to system stakeholders [Oppenheim, 2011].

There is arguably still a lack of clarity in the research community regarding lean thinking in PD, perhaps because many publications came from studies of practice [Hoppmann et al. 2011]. In some cases LPD methods may not address PD needs—for instance because they do not account for iteration. Nevertheless, research points to the potential and demonstrated benefits (e.g., [McManus, 2005]).

2.3. Value and Lean PD

The relationship between value and the methods of Lean PD is not straightforward. A starting point is the definition articulated in several articles reviewed by Browning [2003]:

$$\textit{Value of a system} \propto \textit{performance of the system / cost of the system} \qquad [1]$$

Where both performance and cost may have several dimensions. One interpretation of Eqn. 1 is that reducing PDP waste, e.g., through application of lean methods, increases value of a design by reducing the cost of generating it. A related view is that value is what would remain if all waste could be removed. This is suggested by Womack and Jones' [1996] categorization of work into three types: Value added, required non-value added, and unnecessary non-value added. These residual definitions of value are useful from the lean implementation viewpoint because it is easier to identify and quantify waste in a process than to pin down the value added. However they can obscure certain complexities.

Firstly, LPD is not only concerned with efficiency and waste reduction, but also with enhancing capability to add value [Rouse and Boff, 2001][Browning, 2003]. One important aspect of this is better understanding and, where possible, reconciling conflicts in stakeholder needs. For instance, delivering system performance that exceeds actual needs does not always add value, and may be detrimental in terms of time, cost and performance for other stakeholders. In the requirements process it is therefore important to consider Measures of Effectiveness (MoE), which consider how a system satisfies stakeholder needs in the context of use, alongside Measures of Performance (MoP), which focus on specific behaviours or functions of the system alone, are often internal to the system, and usually are easier to define and measure [Green, 2001]. One way to develop a thorough understanding of stakeholder needs is through development of an effective Concept of Operations (ConOps), a document which describes the system characteristics and operation concept and whose development can help to consider and align stakeholder expectations before the requirements process commences [Mostashari et al. 2012].

Secondly, knowledge work in PD is very different to the production systems from which lean originated [Browning et al. 2006]. In the context of value, key differentiators include:

1. **Unclear distinction between value and waste.** For instance, paying great attention to minor details of a design might seem wasteful if downstream activities are waiting for information –

yet attention to detail can create desirable products, or perhaps avoid disastrous mistakes. Thus, eliminating waste perceived by some stakeholders may not yield overall improvements.

2. **Ambiguous mix of necessary and unnecessary rework.** Waste in PD is not always caused by performing activities that are strictly unnecessary. It is often associated with activities where the inputs later change in a way that could not be avoided. This occurs frequently in PD. For instance, rework might be accepted as the likely consequence of concurrency needed to reduce lead time. Progressive creation of knowledge can reveal problems in the emerging design, rendering earlier decisions and activities performed in consequence invalid. In this case, apparent waste is caused by necessarily revisiting activities that may have been timely and appropriate when first attempted [Browning, 2003].

3. **Contingency and subjectivity of value.** The value of a system over its lifecycle will depend on many contextual factors [Browning and Honour, 2008]. Different stakeholders often have conflicting perspectives on value [Rouse and Boff, 2001]. Some stakeholders may receive loss when a system is implemented. Handling such conflicts is especially challenging in cases such as major capital projects where there is no one clear customer, so the needs of many stakeholders must be given serious consideration. Additionally, there is often no crisp threshold above which a specific stakeholder concern is satisfied, which creates great difficulties in establishing unambiguous measurements of value. Single measures of value such as performance/cost ratios do not indicate how the mix of value delivered by the PDP is influenced by its context, and thus do not account for externalities and conflicting perceptions of value. To illustrate why this is important, consider an organization that creates a new product. The value of that product will be determined by success in the marketplace. Multiple factors contribute, including time-to-market, design and production costs, alongside concerns such as quality and style. Typically some of these factors are in conflict, so the company must aim for a particular mix in its product strategy. This in principle cascades to determine PDP objectives. Ultimately, value will not only depend on whether the PDP meets those objectives, but also on the earlier

decisions that locked in value potential. Whether the potential is realized will depend on the market [Cook and Wissmann, 2007]: the product's positioning given competitors' decisions; the customers, who decide which products are desirable and which are not; and the changing technology landscape.

4. **The need to consider timeliness and scope of value contributions**. These important considerations may be illustrated by examples. In terms of timeliness, there is often a trade-off between maximizing immediate value, and accepting a short-term penalty to invest in a potential opportunity. In terms of scope, one common challenge is balancing the need to maximize value for each individual customer by customizing a product to their needs, vs. developing common components and platforms that can benefit many customers. These examples, and the previous discussion, highlight that hard-to-measure system ilities such as flexibility and adaptability can positively impact the value of a design, although they also incur costs to implement [Chalupnik et al. 2014].

Given all these issues, decompositions of value to a small number of concrete measures at the PD level may over-emphasize the role of PDP performance and obscure the systemic nature of value creation. In practice it is nevertheless necessary to draw a boundary of analysis somewhere, e.g., around the PDP, or around a particular sub-process, to make improvements practicable.

The points made in this subsection about the nature of value in PD are summarized in Table 2.

Table 2. Issues concerning value and its creation in complex system PD

Multidimensionality of value	Value created by a process or organizational unit is multidimensional; the relevant dimensions are determined by the unit or process's context.
Subjectivity of value	Value has different meaning to different stakeholders. The targeted mix and prioritization of value objectives for any (sub)process are the result of a decision that might be optimized.
Capacity for value creation	Value is only realized if its aspects are all delivered by the respective parts of the organization, and if they are successfully integrated.
Contingency of value	Value is only realized if the mix turns out to be appropriate, given unpredictable factors such as market context.

2.4. Summary

Considering the issues outlined above, the value resulting from PD can be understood as: *The* *degree to which a capability satisfies all relevant stakeholders, is delivered to them according to product or service quality, cost, and timeliness requirements, and is developed by performing effective and efficient processes that design and produce the satisfying capability within their budget and time constraints.* Considering Table 2, a value-focused approach to PD should recognize the importance of: (1) Identifying a value proposition; (2) decomposition of the value proposition into realizable requirements; (3) assignment of requirements across the parts of an organization or process; (4) generation of value within each part of the organization, considering relevant interdependencies; and (5) integration of value contributions.

3. Roles in the value delivery system

For value thinking to be useful in improving complex system PD, it should provide a framework explaining how each activity contributes to generating which sort of value [Chase, 2001]. In principle, this could allow optimization of the process towards desired value contributions. Chase thus proposes a four-level framework to describe elements in the value delivery process [Chase, 2001]. The first is value *perspective*, which identifies to whom value is delivered, such as customer, end user and organization. The second is the *entity* which produces value, such as activities and people. On the third level, Chase adopted Slack's *attributes* for value such as quality, time, cost and risk [Slack, 1999]. On the fourth level, Chase argues that attributes can be measured using quantitative or qualitative *metrics*.

The present article builds upon these ideas. Value definition, creation, and delivery are analyzed by considering the PDP as a channel connecting design process participants with other system stakeholders, or design activity as the channel connecting producers and recipients of value. A model is accordingly developed comprising three main roles: definition, creation and delivery. According to this model, the recipient of value holds the value *definition* role, determining 'what is considered valuable?' All stakeholders are value recipients, including customers, shareholders, employees, and the organization. The *creation* role is fulfilled by entities that create value due to characteristics they possess (such as specialist knowledge), or when a value-creation mechanism is adopted (such as a particular activity being undertaken). The main questions regarding value creation are ‘what creates value in PD?’ and ‘what enables value creation?’ Finally, the *delivery* role concerns carriers and indicators of value. The main questions here are ‘how and where is value embodied?’, ‘what are the attributes of these carriers that represent the value?’, and ‘(how) may the levels of value be understood and measured?’

The value creation process may be viewed as a cycle, in which participants fulfilling the creation role produce value, based on requirements set by the holder(s) of the definition role, and deliver it to the same. Capacity to generate value is related to the functional and technical capabilities of a process or organization, including the availability of suitable knowledge assets, experience, processing resource, and technology to perform the job at hand. The cycle closes when the definition role receives value. Feedback may be provided, e.g., through requirement changes that cause rework. Thus, all three roles are interconnected and interdependent, and agreement must be reached between how value is defined and what can be delivered.

Value creation requires a complex, multi-layered system of recipients, sources, and carriers. For instance, a designer may have a value creation role, performing an activity to generate information needed by her colleagues. The same designer might be the recipient of value created by a methods team, namely the tools she uses to perform her work. These tools deliver value because they reduce the time to complete a job. To give another example, the organization receives value from structured procedures to coordinate work, because those procedures enable efficiency. These examples show how value can be created either by contributing to design of a system that has certain desired properties or by allowing this to happen more effectively. A critical point is that it is not sufficient for an individual to create value for another within their company. To avoid the waste of wheels spinning without traction, value must accrue to the customer and hence the organization. This may be articulated as the principle of value pull.

Following subsections further develop the model with reference to concepts in the literature.

3.1. Definition

The definition role is the main driver of value creation, since it determines performance objectives.

3.1.1 Stakeholders

Different stakeholders may define value in different ways. As discussed earlier these should be carefully balanced or reconciled where possible, and the result of this process should be captured in system requirements [Bijan et al. 2012]. In the following we focus on four main stakeholder groups that typically contribute to defining PD value, building on the categorization suggested by Slack [1999]. This list should not be considered exhaustive; depending on the PD context other stakeholder groups will also be influential in determining the definition of value.

1. **Customers** are perhaps the most commonly-considered value stakeholder in PD (e.g., [Browning et al. 2002]), and can be organised into two types:
   a. ***Internal customers*** are consumers of the process output further along the value stream [McManus, 2005].
   b. ***External customers*** include the users, purchasers and operators of the product, service, or system. Browning [2003] argues that value for users is driven by process and product attributes, namely cost, timeliness, and performance, and that it depends on customer preferences and market alternatives. Preferences are driven by a mix of functionality, physical characteristics and non-utilitarian, emotional associations that affect how a product or service is perceived and what it symbolises to the customer [Derek et al. 2003].
2. **Shareholders** receive economic gain, for instance facilitated by more profitable products or increased market share [Higgins, 1998].
3. **Employees** receive value from PD through benefits such as compensation, interesting work, pride, and career advancement [Beauregard et al. 2008]; [Patanakul and Shenhar, 2010].

Because employees also play a central role in creating value (§3.2.1) these benefits can create a virtuous cycle enhancing the value capacity of a process or organization.

4. **Organizations** receive value from PD including financial benefits, new market opportunities, improved strategic positioning, organizational learning, enhanced name and brand recognition, and development of relationships [Patanakul and Shenhar, 2010]**.**

As mentioned earlier, a key challenge in product development, especially complex systems PD, is to comprehend and balance the often-conflicting requirements from different stakeholders [Oppenheim, 2011]. For instance, a customer expects new products to correspond to their values and lifestyles. They may consider a product's value to be related to its performance and price. Equally, most organizations are concerned with the implication of a new product on their existing production system. Finding the right balance can give a competitive edge in the market [Edvinsson, 1997], while deficiency in understanding stakeholder needs and potential conflicts can result in sub-optimal design choices. It is also important to consider that some influential stakeholders may perceive value loss from PD – for instance because of environmental impact. In such situations it is necessary to seek a balance between the positive and negative impacts.

3.2. Creation

There is no detailed, universally-applicable recipe for value creation [Pessôa et al. 2007], and identifying the specific actions that create value is a challenging task [Murman, 2002]. Several models have been developed to clarify how value is created in PD. For instance, Kotler and Keller [2006] suggest that value propositions are the output of objects such as physical products, services, experiences, persons, places, properties, organizations, or information. According to Zhai [2009], value creation in PM can be seen as the conversion of resources into project outputs. In the context of LPD, Chase suggests that value creation may be viewed as a function of three main components: activity quality and efficiency information, risk, and ease of information flow. Murman et al. [2002] propose an iterative value creation framework, which includes: value identification, value proportion, and value delivery. Here, we consider the sources of value and enablers of its creation.

3.2.1. Sources

The literature discusses three ways of perceiving the sources of value in PD:

1. **People,** referring to roles or functions rather than individuals, are said to create value through undertaking specific actions:
   a. ***Management*** creates value by implementing strategies that respond to market opportunities by exploiting a company's resources and capabilities [Penrose, 1959]. Furthermore, management adds value by decision-making on issues such as logistics, capacity, team structure, and requirement trade-offs. These can often be cast as resource allocation problems. For example, at the enterprise level, Beauregard et al. [2008] studied how effective coordination between resources and activities is needed to create value.
   b. ***Knowledge assets,*** including design teams, engineers, and other employees, create value when they apply their technical knowledge and professional skills to address design problems. For instance, Carlucci and Schiuma [2006] studied how knowledge assets can most effectively create value when appropriately aligned to organization performance objectives. Sorli et al. [2012] discuss how designers can focus innovations and reduce their overall processing time by applying principles of Knowledge Based Engineering (KBE).
2. **Processes** are sets of actions, or chunks of development work. Processes may be considered on different levels of abstraction, such as activities or subprocesses. They are related to the "people" category discussed above in that people perform the actions that comprise a process. In general, a process might be considered to add value due to production of deliverables that meet requirements. It has been suggested that value created by a process can be viewed as the aggregate of value created by its activities or individual actions [Browning, 2003] [Chase, 2001] – while noting that such a calculation would not be straightforward in practice, due to the different forms of value created within a process and the interactions in integrating them.

Browning aims to address this issue by proposing that processes should be viewed as adding value by creating information that progressively reduces design performance risk [Browning et al. 2002].

3. **Methods and Technology** refers to tools, technology and techniques adopted across the product lifecycle, such as Product Lifecycle Management systems, as well as design technologies such as simulation tools, and methods and procedures that capture knowledge about how to perform and coordinate the work. Such resources enable certain tasks that would not otherwise be possible, or increase the efficiency and effectiveness of process and people, as in the example at the start of §3. They add value because they reduce the cost of generating deliverables.

These three categories highlight three interrelated facets of value creation. Methods and technology support the people who execute the actions that form the processes which deliver value. The facets should thus be considered together when discussing the sources of value in PD.

3.2.2. Creation mechanism

People, process, and methods and technology work together to produce value. The value created may depend on characteristics of the source, for instance the capabilities and experience of a design team, complexity thus coordination difficulty of a process, or maturity of a design technology. LPD research offers practices and approaches to assist value creation, which are discussed in §4.

3.3. Delivery

Delivery links the definition role with the creation role, ideally ensuring that the level of value created by the sources meets the requirements of recipients. In the framework, value delivery is decomposed into three issues: *carriers*, *attributes* and *indicators*.

3.3.1. Carriers

When value is created, it is embodied in, and carried by, elements such as the design recipe, people who hold knowledge, financial assets, and processes. Carriers are thus the link that connects value sources with value recipients. Carriers and their value may be transient, e.g., when design information is created to enable a downstream activity, or cumulative, e.g., when new data or experience is added to a knowledge base. Four types of carrier were identified in the literature:

1. **Design information,** which conveys design specifications or is used during their development.
2. **Knowledge assets**, referring to individuals who possess knowledge required during PD.
3. **Process**, referring to the activities and tools used to create the design.
4. **Delivered product/system,** as defined by the recipe which is the output from PD.

3.3.2. Attributes

Attributes of a carrier determine the type and amount of value it represents. For example, attributes of design information include its timeliness and quality. Numerous value attributes have been discussed in the literature, as suggested in §2.1.

3.3.3. Indicators

Some attributes associated with value may be measurable to indicate the performance level of the PDP and thus influence decision-making. Some of these measurable indicators focus on attributes of individual activities, while others concern the delivery role as fulfilled by the entire PDP. The latter allow value attributes to be assessed early in the PDP. The relationship between indicators, attributes, and carriers is illustrated by examples in Table 3.

Making effective use of indicators to assess value attributes can be challenging. This arises in part from the uncertainty and ambiguity associated with their measurement, and in part from the lag time between estimating them during PD activity and obtaining the actual result. Furthermore, many indicators depend on subjective expert assessments. Indicators also focus on individual carriers and thus the contribution of individual sources, while value is largely dependent on the relationships between them. To be most useful, value indicators can be placed into the context of a measurement system. These are discussed further in §4.3.

Table 3. Examples of value attributes and indicators for different types of carrier

Type of value carriers	Attributes of carrier	Indicators of attribute (e.g.)
Design information	Timeliness	Planned /Projected delivery date of information
	Quality	Compliance of specification to requirements = Total number of non-compliances / total number of requirements x 100%

		Has the information been validated?
Knowledge assets	Experience	1/ Number of engineering errors made
		Number of successful design stages completed
	Performance	Innovation: 1/% of design reuse
		Total number of design changes raised / Number of design changes raised after release to manufacture
		1 / Lead time for performing a certain activity
Process	Effectiveness	Productivity = value of output/cost of department
		Benefit/cost of a task
	Flow and inventory	1 / mean queue size = 1/num. activities waiting for information
		1/ Time information spends waiting to be processed
	Performance	Budgeted cost of work performed/actual cost of work scheduled
		Ratio of useful work performed to the total effort expended
		Number of milestones (gate reviews) completed for a given type of project/ project man-hours (resources)
Delivered product or system	Customer satisfaction	Sales volume
		Market share
		Customer value [Slack, 1999] = ∑ [N x (1-R) x F(t)] / C, where: R = risk N = importance of the need F(t) = availability relative to need date C = cost of ownership. Summation is made over all needs.
	Cost customer will pay	Cost of product or system
	Timeliness	Time of delivery to market relative to need

4. Value-oriented approaches in Lean PD

This section elaborates the framework by integrating discussion of methods that aim to improve PD processes from the value perspective, with a primary but not exclusive focus on approaches in the lean literature. In the following subsections, the approaches are organized into five categories:

1. **Lean/value practices** thought to enable value creation in LPD.
2. **Implementation approaches** that suggest how to bring such practices into play.
3. **Mapping tools** that support understanding and improvement of specific parts or aspects of the PD process from a value perspective.
4. **Measurement systems** that concern tracking and thus enhancing effectiveness of LPD.
5. **Success factors,** which are contextual characteristics thought to affect value creation.

4.1. Lean/value practices

Notwithstanding that lean should be viewed as an interconnected system and philosophy, not just a "set of methods" [Liker and Morgan, 2006], numerous practices have been developed to assist value creation in lean PD. For instance, Oppenheim lists 147 practices formulated as do`s and don'ts that are thought to help achieve lean in systems engineering [Oppenheim, 2011]. Many LPD practices are not new, but have been adopted because they are thought to help achieve lean principles. A number of publications have focused on classifying practices with the intention of clarifying their relationships. In one such article, practices are organized into 6 main principles: supplier involvement, simultaneous engineering, cross-functional teams, integration of activities, a heavyweight team structure, and strategic management of projects [Oppenheim et al. 2011]. In another, Reinertsen [2009] proposes that lean, as the "new paradigm in PD", emphasizes three main principles: small batch transfer, rapid feedback, and limited work-in-process inventory. These focus on enhancing flow, which is thought to improve value generation by increasing efficiency, but also through secondary effects – such as reducing information-in-process which may help identify problems quicker and thus reduce the scope of iteration loops [Reinertsen, 2007]. Liker [2004] suggests lean components can be grouped into three categories: skilled people, tools and technology, and process. To integrate lean practices into the value framework, Table 4 summarizes and groups them according to their focus on the levels of value delivery discussed in §3.2.1. This table organizes the main ideas, although is not exhaustive.

Table 4. Summary of 67 key lean/value practices in the LPD literature, organised hierarchically according to their foci, and some exemplar publications providing more information.

1. PEOPLE

1.1. Team composition	**1.2. Working environment and motivation**
Associate resources with objectives *[Carlucci and Schiuma, 2006]*	Encourage decision-maker interactions *[Carlucci and Schiuma, 2006]*
Assemble a core team *[Oppenheim 2004]*	Build consensus of team on program *[Oppenheim, 2004]*
Establish cross-functional teams *[Parry et al. 2008]*	Promote project transparency *[Eskerod, 2009]*
Have chief engineer to lead and integrate PD *[Oppenheim 2011]*	Use common reference frame & PM model *[Eskerod, 2009]*
Ensure top management involvement *[Eskerod, 2009]*	Centralize discussions, eg. in war rooms *[Oppenheim, 2004]*
Train and enhance leadership *[Garza, 2005]*	Have an open design space *[Clark and Fujimoto, 1989]*
Ensure managerial integration of engineering specialties [Sage and Lynch, 1999]	Visualize and use visual control *[McManus, 2005]*
Develop appropriate architecture for the system [Sage and Lynch, 1999]	Use metrics to motivate the right behavior *[Oppenheim, 2011]*
	Responsibility-based planning

2. PROCESS

2.1. Requirements and value definition	**2.2.3. Execution: Avoid unnecessary work**
Seek consensus on customer value *[Oppenheim 2011*	Eliminate unnecessary documents *[McManus, 2005]*
Define value, eg. value breakdown structure *[Pessoa et al, 2007]*	Eliminate unnecessary reviews & approvals *[McManus, 2005]*
Provide clear definition of requirements *[McManus et al. 2007]*	Produce information in the right format *[Chase, 2001]*
Define internal customers & requirements *[Oppenheim, 2004]*	**2.2.4. Execution: Monitoring & reviewing**
Define the value of activities` outputs *[Oppenheim, 2011]*	Plan effective metrics *[Oppenheim 2011]*
2.2.1. Execution: Maintain steady flow	Monitor, measure, anticipate TPMs *[Browning et al. 2002]*
Focus on enabling uninterrupted flow *[Oppenheim, 2004]*	Monitor requirement satisfaction *[Hoppmann et al. 2011]*
Divide work into small batches *[Furuhjelm et al. 2011]*	Balance reviews *[McManus, 2005]*
Pull information, e.g. Just-in-time *[Smith and Reinertsen, 1991]*	**2.3. Learning and improvement**
Maintain discipline in execution *[Oppenheim, 2004]*	Use a bottom-up improvement strategy *[Oppenheim 2011]*

Balance human vs. computational workload *[Pepe et al. 2011]*	Apply relentless improvement *[Rudolf and Paulisch, 2010]*
Reduce buffer variation *[McManus, 2005]*	Collect & visualize performance indicators *[Chase, 2001]*
Eliminate bottleneck *[McManus, 2005]*	Visualize process, eg. Value stream mapping *[McManus, 2005]*
2.2.2. Execution: Manage iteration	Apply techniques such as 7 wastes and 5S *[Parry, 2008]*
Sequence activities to maximize value *[Browning, 2003]*	Use failure as an opportunity to learn *[Oppenheim, 2011]*
Optimize iteration loops (e.g. using DSM) *[Oppenheim, 2011]*	Ensure progress is visible to all *[Oppenheim, 2011]*
Front-load the design and implementation *[Oppenheim, 2011]*	
Test then design *[Catic and Vielhaber, 2011]*	
Apply simultaneous engineering *[Hoppmann et al. 2011]*	
Overlap problem solving activities *[Clark and Fujimoto, 1989]*	
Integrate with suppliers & customers *[Bersnahan et al. 2006]*	
Identify & mitigate technical uncertainty *[Browning et al. 2002]*	
Strive for process integration, e.g., integrate program planning, execution, and continuous improvement [Grady, 1994]	

3. METHODS AND TECHNOLOGY

3.1. Methods and tools	**3.3. Design issues**
Question methods and tools *[Browning, 2003]*	Promote awareness of cost *[Browning et al. 2002]*
Standardize methods and tools *[McManus and Millard, 2002]*	Base decisions on net impact *[Browning, 2003]*
Adapt methods & tools for people & process *[Oppenheim, 2011]*	Remove redundancy & simplify *[McManus and Millard, 2002]*
Avoid complex monument tools *[Oppenheim, 2011]*	Establish product families *[McManus et al. 2007]*
	Reuse common parts and designs *[Garza, 2005]*
3.2. Inventory and information	Integrate lifecycle concerns *[McManus, 2005]*
Manage inventory effectively *[Reinertsen, 2009]*	Consider manufacturing and assembly *[Garza, 2005]*
Promote, re-use, and share program assets *[Oppenheim, 2011]*	Design to allow modification *[Rudolf and Paulisch, 2010]*
Have a global database [*Londono et al. 1992]*	Integrate systems thinking *[Rudolf and Paulisch, 2010]*
	Utilize strategies and tools to support effective integration *[Browning, 1998]*
Ensure availability of information *[McManus, 2005]*	
Define format for information transfers *[Oppenheim, 2004]*	

4.2. Implementation approaches

The journey of an organization towards LPD and its value orientation can be difficult, due to the many interrelated practices and cultural transformation required [Liker and Morgan 2006]. Some authors discuss frameworks that bring together certain practices into LPD implementation steps, or attempt to clarify how practices fit together into a holistic system. Four examples are summarized in Table 5. The first two consider understanding and enhancing value in a broad sense. The third focuses on reducing rework in concurrent engineering. The final two frameworks in the table focus more narrowly on applying lean principles for effective process logistics – which has been defined as "ensuring that the positioning of engineering resources is appropriate to support the flow of intellectual work in process" [Beauregard et al. 2008]. The idea in these latter articles is to bring PD closer to the regimented and efficient flow of lean production. A key question is whether the methods proposed to minimize the uncertainty associated with engineering jobs will prove sufficient to allow application of lean flow principles. Oppenheim [2004] suggests this depends on project characteristics including scale and novelty. Highlighting another challenge to implementing lean flow in PD, Siyam et al. [2013] found that some practitioners believe the required standardization could constrain innovation.

Table 5. Example LPD implementation approaches

Approach	Approach description
Value strategy in SE [Rouse and Boff, 2001]	Based on elaboration of value positioning of an R&D organization as a balance between quality, productivity and innovation. Proposes a 7-step value strategy process including defining value, measurement and benchmarking, and defining an action plan including strategies for change, decision processes, and consideration of organizational implications.
Lean principles for innovation [Cooper and Edgett 2005]	Seven principles of lean are proposed for product innovation: customer focus, front-end loaded spiral development, a holistic approach driven by effective cross-functional teams, metrics, accountability and continuous improvement, focus and effective portfolio management, and a flexible and adaptive, scalable and efficient innovation process.
Set-based framework for product development [Kennedy et al. 2014]	Proposes that wasteful rework in PD can be reduced by identifying knowledge gaps early in a program and not proceeding until they are all closed, applying set-based concurrent engineering to ensure that all interfaces are feasible, and use of A3 thinking incorporating trade-off and limit curves to systematize and transfer these insights across consecutive projects.
Lean PD Flow [Oppenheim, 2004]	Proposes PD work can be organized to be pulled at a steady pace according to takt periods to minimize rework, backflow, or information inventory. Proposes uncertainties should be mitigated, and flow maintained through regular integrative events, dynamic resourcing, and strong leadership.
Lean Logistic Approach [Beauregard et al. 2008]	Proposes engineering jobs can be treated separately, as WPs that must be processed through a stream of tasks. Proposes clustering of jobs according to resource requirements, prioritization, and synchronization of flow according to bottleneck resource.

4.3. Mapping methods

Value-oriented mapping methods are intended to assist practitioners in understanding their processes, systems and organizations from a value perspective, as well as predicting and optimizing performance [Leon and Farris, 2011] (Table 6). One well-known method is value stream mapping (VSM), which originated in lean production and has been adopted by LPD [McManus 2005]. VSM is a process mapping-based method for optimizing flow and pinpointing the root causes of waste, but has limited capability to account for design iteration and complex concurrency. Another example is the Design Structure Matrix (DSM), which has been applied to study many issues related to complex interdependency in PD. In the context of LPD, DSM has for instance been used to show how information dependencies cause wasteful rework if tasks are improperly sequenced [Browning 2003]. Bertoni et al. [2013] develop an approach to help engineers understand the assessed value of an emerging design, by color-coding parts of the design in a CAD system.

Table 6. Examples of value-oriented mapping methods

Method	Description
Value Activity Map [Chase, 2001]	Matrix that relates PD activity and information to specific value metrics.
Value Stream Analysis/Mapping (VSA/M) [Millard, 2001] [McManus and Millard, 2002]	Visualize and analyze the cause and effect of associating the knowledge asset with organization objectives.
Activity DSM [Browning, 2003]	Maps dependencies in process; simulation provides guidance to optimize

	task sequence for minimizing wasteful rework iterations.
Knowledge Asset Value Creation Map (KAVCM) [Carlucci and Schiuma, 2006]	Diagram mapping the stream of activities that adds value to the final product of a process.
Value flow mapping [Cameron et al. 2007]	Approach to map flows of value between stakeholders, showing different value types and self-supporting cycles of value.
Value visualization in CAD [Bertoni et al. 2013]	Color-codes parts in a CAD system according to assessed value, relative to a baseline design or to a specified target.

4.4. Measurement systems

Measurement systems aim to assess the capacity of an organization to add value. Rouse and Boff [2001] argue that such benchmarking is essential to implementing a value strategy effectively. Measurement systems may be considered improvement approaches because a focus on measures encourages an organization to satisfy them [Haque and Moore, 2004], and because they ultimately enable continuous improvement.

Measurement systems differ from value indicators discussed earlier in that they bring together several indicators to track the effectiveness of a project or organization. Some of the examples summarized in Table 7 focus on purely objective measures defined by formulae such as cost/time, while others aim to integrate these ideas with the intangible aspects of value delivered by a process. A common theme is the need for a multidimensional system, including in some cases conflicting definitions of value. Methods such as balanced scorecard, multi-attribute utility theory and analytic network process may be useful to aggregate value aspects to support decision-making.

Table 7 Summary of value-oriented measurement systems discussed in the literature

Article	What is measured?	Key ideas
[Cusomano and Nobeoka, 1992]	Characteristics that create value	Reviews contingency studies that attempt to explain what sort of organization creates what sort of value in the automotive industry, in terms of metrics related to (1) product strategy, (2) organization structure and process; and (3) product/process/company performance.
[Browning et al. 2002]	Value added progressively during design	Adding value in PD equates to activities creating information that reduces risk of not meeting performance targets. Proposed method integrates successive estimates of technical performance measures that have progressively reducing uncertainty, thus tracking rate of risk reduction, therefore of value creation.
[Browning and Honour, 2008]	Life Cycle Value of enduring systems	Focus on combining viewpoints of different stakeholders and accounting for preferences that may change over time.
[Webb, 2003]	Project progress (Earned Value Method)	Visualize project progress in terms of performance against cost, schedule and delivery; understand when corrective action is required.
[Thomas and Mullaly, 2007]	Value of project management (PM)	Focus on the need to synthesize financial value (e.g. ROI, quality/cost, etc.) with intangible aspects, and to consider contextual factors that may affect measured impact, to isolate the effect of PM as the object of study.
[Zhai, 2009]	Value of mega-project management	Considers project management value as enabling delivery of project value, and providing intangible benefits. Presents ways PM value can ‘spill over’ through impact on stakeholders over system life . Claimed to be “mostly-measurable”.
[Tribelsky and Sacks, 2010]	Effectiveness of information flow during construction design	Information flow tracked via logs in document management system. Changes to successive versions of engineering drawings analyzed automatically. Used to calculate metrics to locate flow problems that reduce value - including

		bottlenecks, rework, large batch sizes, and excessive work in progress.
[Beauregard et al. 2008]	Progress on lean implementation	System for comparing flow-focused indicators of engineering jobs in progress against a previously-set baseline. Based on set of measures such as touch time, intellectual work in progress, wasted setup time, etc.
[Haque and Moore, 2004]	Aspects of PD performance, aligned to encourage lean thinking	Seven metrics at enterprise level (e.g. compliance to requirements, schedule performance, inappropriate changes etc.) allow comparison of leanness across products; are decomposed into more specific measures suitable for comparing similar products/processes. Aggregation system not defined.

4.5. Success factors

Success factors are organizational or contextual characteristics thought to impact the effectiveness of value creation in complex system PD. For instance, Browning [2003] and Honour [2010] argue that effective system engineering is important; Yassine and Wissman [2007] identify 12 ways that effective system architecture can influence value creation. Patanakul and Shenhar [2010] propose that appropriate organizational strategy and long-term goals are critical influences on effective value creation. More success factors are listed in Table 8, organized according to the value cycle roles.

Table 8. Example success factors for value delivery

Role	**Issues**	**Example success factors and articles that discuss them**
Definition	What affects value perception and definition?	• Complexity of needs [Oppenheim, 2004] • Customer & supplier expectations & experience ([Murman et al. 2000; Browning et al. 2002]) • Company strategy [Buyukozkan and Feyzioglu, 2004] • Market and competition [Germanu et al. 2009]
Creation	What affects value creation and level of value created?	• Complexity of product and process ([Oppenheim, 2004]; [Pessoa, 2004]) • Novelty of product [Browning et al. 2002] • Market and funding uncertainties [McManus et al. 2007] • Infrastructure and technology [Murman et al. 2000] • Evolving regulatory and political context [McManus et al. 2007]
Delivery	What affects capture, measurement and delivery of value?	• Technology maturity [McManus et al. 2007] • Appropriate selection of carrier to be measured [Haque and Moore, 2004] • Forecasting ability [Beauregard et al. 2008] • Frequency of measures being reviewed and revised [Haque and Moore 2004]

5. Discussion and critique

The ideas reviewed in previous sections suggest that organizations need to define what they mean by value as a first step in improving their performance through a value approach. They should consider the needs of different stakeholders and take into consideration quantitative and qualitative aspects of value – combining perspectives such as desired product or system characteristics, financial gain, organizational learning, and process efficiency. After establishing an understanding of value, it can provide common ground on which multiple disciplines may communicate and, in principle, identify and manage tradeoffs [Randmaa et al. 2011]. Value creation can be enhanced by implementing best practices and improvement approaches, many of which may be found in the LPD literature. Finally, characteristics of an organization that affect its value creation capacity, as well as the value levels associated with an emerging system during its development, should be measured and controlled. The framework is summarized graphically in Figure 1. It may help to further integrate an understanding of system value and its creation with LPD. Consideration of literature on value and SE also reveals some apparent gaps in LPD thinking. These are discussed below.

5.1. Approaches should address differences between PD and manufacturing

PD and manufacturing differ [McManus and Millard, 2002][Browning, 2003]. Many LPD articles recognize these differences, yet they are not tackled thoroughly. This can be seen in Table 4, which illustrates how many best practices for lean PD have been transferred directly from manufacturing. Examples include just-in-time and maintaining a steady pace of progress. These methods often assume linear, steady and deterministic processes with accurate forecasting, which is often not possible under the high levels of uncertainty and ambiguity that exist in complex system PD. Some LPD principles may need to be reshaped accordingly.

5.2. Approaches should integrate insights from PD practice and related research

Some of the limitations of lean PD could be addressed through a closer integration with existing perspectives on complex system PD process management. For instance, PD research has developed approaches to support each step of the design process from initial idea to fully-documented design [Ćatić and Vielhaber, 2011]. In contrast, much of the lean PD literature does not specifically relate to the challenges particular to each phase of the PDP. As shown in Table 4, there is instead a focus on generic principles, metrics, and best practices intended for application to generic situations having moderate levels of complexity and good forecasting capability.

5.3. Approaches should consider value of the product or system that is delivered

Early transfer of value ideas to PD focused on developing economic models and quantifying customer value (e.g. [Higgins, 1998], [Slack, 1999]). Afterwards, research shifted to information flow management and risk identification (e.g. [Browning et al. 2002]). Currently, lean PD research is mainly focused on the delivery process of value, tackling cost and time of the process. Value associated with the design that is generated, such as manufacturability, durability and other ilities, has not yet been fully integrated. Cost of product usage is often not emphasized. Therefore, although lean/value approaches aim to provide holistic frameworks to enhance the enterprise on different levels, they are quite narrow in applicability in comparison to the wider understanding of value and its delivery in SE and related fields, which is summarized in §2 and §3.

5.4. Approaches should consider the end-to-end value process

The value cycle framework reveals a lack of linkage between the superset of issues discussed. For instance, some articles tend to focus on enhancing the understanding of value (§3) thus focusing on the definition role of the framework, while others develop applications of lean to PD (§4), thereby focusing on enhancing value delivery. There is very limited discussion in the literature on how to integrate the different parts of the problem and on elaborating the cause and effect that relates the different elements of value delivery. Further research could address this by taking a holistic, network-oriented view of value creation.

5.5. Approaches should consider how value is aggregated

It remains challenging to explain how the different sorts of value added by parts of a process aggregate to value as perceived by the system stakeholders. This may be due to the high levels of ambiguity in PD, and because value may be defined in very different ways at different levels and functions in the organization. The difficulty is exacerbated if measurement culture is not embedded in an organization. Consequently, there is a need to develop improved methodologies to understand and evaluate aspects and dimensions of value as added on the local activity level, and to understand how these local measures can be aggregated into higher-level indicators [Murman et al. 2000].

5.6. Approaches should incorporate multiple dimensions of value

LPD indicators as summarized in Table 3 often do not account sufficiently for requirement conflicts and often do not help identify trade-offs in stakeholder needs, including the need to balance positive and negative perceptions of system value. LPD approaches claim to tackle multiple attributes and recipients, yet the methods discussed in §4 often lack a whole-system view, thus may sub-optimize towards individual value attributes and recipients. In addition, approaches either do not include the necessary depth to guide practical application [Chase, 2001], or require many detailed local measures, which can be challenging and time consuming to manage. Finally, as mentioned in §2.1, value perceived by customers includes more than physical, utilitarian components - it also depends on experiences and expectations. However, current LPD literature is centered largely on a utilitarian perspective of value [Gudem et al. 2011].

5.7. Approaches should more explicitly consider lifecycle value

SE aims to produce enduringly valuable systems [Browning and Honour, 2008]. This requires an understanding of lifecycle value, considering not only design and production but also system operation and disposal costs. As summarized in §2.3, requirements also often change over time as stakeholders interact with a system.

Extensive research in value management, life-cycle costing and systems engineering has focused on lifecycle value (e.g [Stanke and Murman, 2002]). Although the need for incorporating the lifecycle value perspective is recognized in LPD literature, there is a need for greater emphasis on concrete methods to balance immediate waste reduction against lifecycle value and the possibility of evolving requirements. For instance, VSM typically focuses on improving well-delineated processes, and does not emphasize how changes to these processes might affect system value later in the lifecycle. In contrast, Browning and Sanders (2012) recently emphasized that a process or an activity should not be improved in isolation, and the overall process and impact need to be considered. According to Browning and Heath (2008), research has also not sufficiently considered the influence of environmental context or organizational contingencies, an oversight which may have limited the overall impact of lean practice.

5.8. Research should continue to seek evidence of benefits to complex system PD

LPD has been described as an ‘unfinished story’ due to a number of shortcomings [Murman, 2002]. Many of these seem critical when considering application to complex system PD. For example, approaches often assume a high level of knowledge, mature technology, well-defined and prioritized requirements, and small design programs. Moreover, some LPD proposals lack much empirical evidence of impact on complex programs, so it may be difficult to justify their implementation in this context. Research should seek more evidence of benefits of lean in complex system PD.

6. Concluding remarks

An understanding of the mechanisms and enablers of value creation is important to allocate resources effectively within an organisation. A number of approaches, methods and practices have been proposed to enhance PD from the value perspective, many associated with lean thinking. This article has contributed a structured literature review on value ideas in complex system product development. The review reveals that although value is a concept frequently mentioned in the PD, SE and especially LPD literature, it may be considered from many different perspectives and lacks a coherent theoretical underpinning. To understand PD value as discussed in the literature requires consideration of many issues that are difficult to synthesize into a single concise definition. This article contributes to the discussion by integrating concepts from the literature into an organizing framework that helps explain the value delivery process, and positions value-oriented methods with respect to it. The framework thus maps current thinking on PD value and highlights opportunities for further research.

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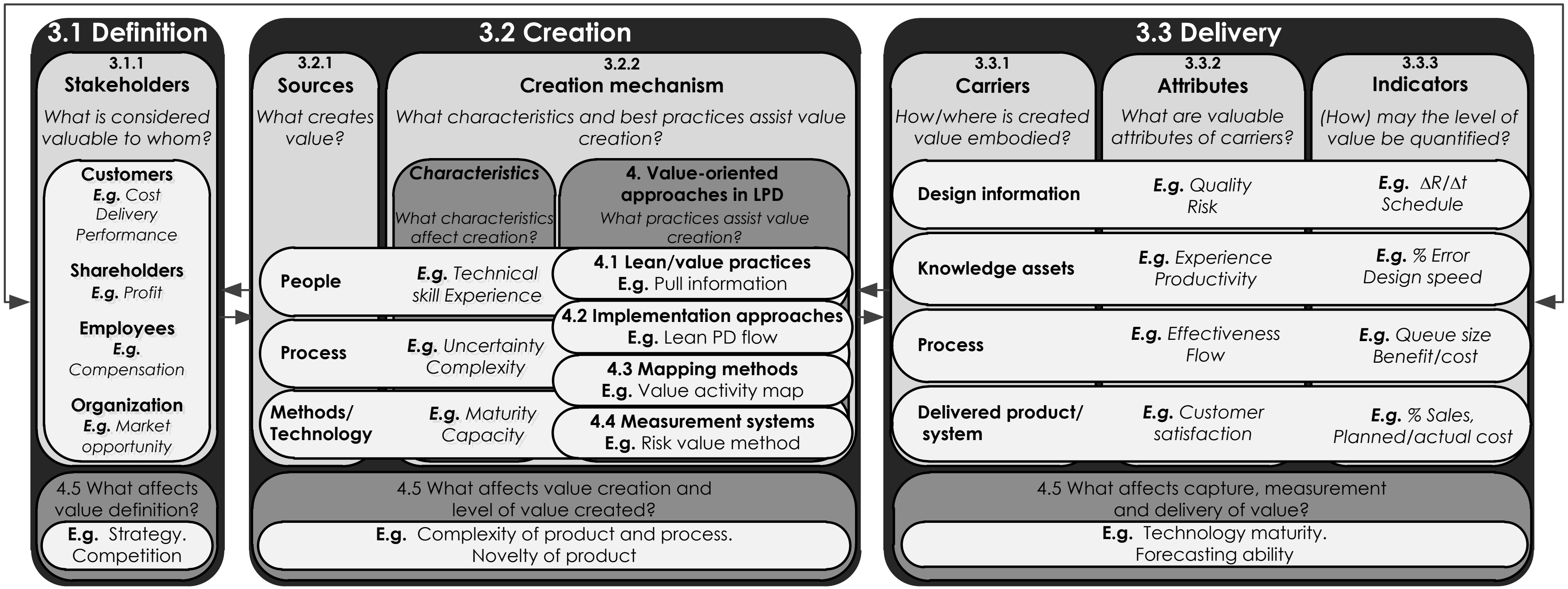

Fig 1. Overview of the value cycle framework emphasizing the roles of definition, creation and delivery. All three roles are interconnected and interdependent, because agreement must be reached between how value is defined and what can be created and delivered. The main logical flow is counter-clockwise, with definition depicted first to emphasise the driving role of stakeholders and requirements in value creation. Numbers in the figure refer to the article subsections in which each concept is discussed. The structure of the framework is introduced at the start of Section 3.