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Co-creation in complex supply chains: the benefits of a Value Driven Design approach

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Abstract In the last decade, as the manufacturing companies have reconsidered the overall concept of goods production, their focus shifted from developing ‘products’ to ‘solutions’. In complex supply chains, the combination of products and services that maximize customers’ and stakeholders’ value can be identified only if manufacturers improve their ability to co-create, establishing more interactive relationships with end users, clients and sub-contractors. Methodologies for Value Driven Design (VDD) are emerging as enablers for cross-functional and cross-organizational knowledge sharing, reinforcing early stages design iterations to emphasize the maturation of the requirements across supply chain levels. This chapter highlights the uptake of VDD in a traditionally protective domain, such as the aerospace sector. It describes methods and tools for value assessment, and points toward the most relevant initiatives in this domain. Eventually, it discusses areas of further research to promote the effective use of the VDD methodology while designing complex engineering systems.

Keywords: Value Driven Design, Engineering design, Customer co-creation, Enterprise collaboration, Systems engineering, Systems design, Value engineering.

Introduction

While the business climate during the twentieth century has forced industries to continuously innovate their approach toward the development of new products (Brown and Eisenhardt 1995), in the last decades the competition on the global market has driven manufacturing companies to reconsider the entire concept of goods production. Competitive advantage and larger market shares are not longer achievable purely through continuous technical improvements; rather, it is neces-

sary to radically rethink aftermarket activities. Manufacturing companies need to consider themselves not only as product sellers but also as service providers (Oliva and Kallemberg 2003). Initiatives such as Functional Products (Alonso-Rasgado et al. 2004), Product-Service Systems (PSS) (Baines et al. 2007) and Integrated Product Service Engineering (Meier et al. 2010) reflect the shift toward broader offerings that include product-related services.

This transition, which has been largely driven by customers, requires manufacturers to gain a deeper understanding of their counterparts' expectations and needs (Woodruff 1997). This triggers radical changes not only in the way the products are offered, but also in the way they are designed and developed (Baines et al. 2007). It is no longer the 'product' that is the result of the design activity, but rather the 'solution'. Developing a 'solution' is not merely a matter of meeting engineering requirements any longer, but it is about finding the best combination of products and services to maximize customers' and stakeholders' value.

Co-creation activities become an imperative in this situation. Knowledge that resides in the domain of customers and users becomes crucial to drive innovation activities (Piller et al. 2011), hence interactive relationships have to be established among producers, users and many other different institutions (e.g., Laursen and Salter 2006) to develop value-adding offerings. Then, as more detailed knowledge about technologies and applications is required earlier in the design process to design product and services in synchrony (Isaksson et al. 2009), consortia of risk-sharing partners are formed to locate educated engineers with Research and Development (R&D) skills, which are normally difficult to find within a single organization (Acha et al. 2004).

Co-creation activities, however, are far from being a reality in complex supply chains. In consortia or risk sharing partners, contracts represent the principal and necessary mechanism for regulating the flow of design information. In the aerospace industry, Isaksson et al. (2013) observed that, even if contractual requirements undergo several negotiation steps when cascaded down to sub-contractors, design information is rarely iterated among supply chain partners at early design stages. To add even more complexity, it has to be considered that companies in such consortia often work in a mode of 'coopetition' (Brandenburger and Nalebuff 1997) which is they 'collaborate with the enemy', simultaneously cooperating in a project and competing in another one. Hence, the developers of sub-systems and components can start working only after they have received validated input requirements from the top level. Under strong pressures to develop faster, better and cheaper products and services, they might even initiate design activities without exactly knowing what their input requirements will be, but only relying on previous experience and a number of assumptions (Isaksson et al. 2013).

Using contractual requirements as the principal communication device poses severe challenges to co-creation. Firstly, even if sub-contractors could ask for preliminary versions of their input requirements to start their work based on those, they might just be too immature, invariably leading to high levels of design changes and corrective rework. In turn, this will lead to unplanned costs and de-

lays, as well as conservative, rather than innovative, design solutions. Secondly, requirements emphasize the requests from the nearest stakeholders, neglecting a broader perspective where the point of view of the higher-level customers, and of the final users, is considered. Moving away from the Original Equipment Manufacturer (OEM), requirements become more detailed and lose connection with the initial customer needs and expectations.

Co-creation in complex supply chain networks requires different means to share information earlier about the intent of a design, as a means to anticipate upcoming needs, sort out major trade-offs, and be ready with the technology at the time needed. The purpose of this chapter is to illustrate how methods and tools for Value Driven Design (VDD) can emphasize the maturation of the requirements across supply chain levels, by realizing more frequent design iterations in an early stage. In turn, this aims to foster co-creation activities and orient early stage design decisions toward value maximization.

The chapter summarizes the definitions for value and VDD, and reviews methods and tools proposed in both academia and industry to support the selection of the best design alternative on the basis of arguments related to the possibility to fulfill the overall customer ‘value’. The chapter also illustrates how VDD techniques cascade down information from the strategic to the technical level, providing means for engineers to benchmark designs on the basis of their capability to fulfil customer and user value scales. It further presents a VDD application example taken from the aerospace context, and eventually describes the main issues related to VDD research and how they are addressed by current research initiatives.

The Multifaceted Meaning of Value

As stated by Browning (2003), “process improvements in product development cannot just focus on waste, time, or cost reduction, but the purpose should be to maximize the product value”. Accordingly, decisions made during design should always add value to the solution space. But what is value exactly? Although value is a unique concept (Day and Crask 2000), the term is often interchanged with other notions, and a widely accepted definition is hard to find.

Miles (1972) first introduced the value analysis concept. A product or service is generally considered to have good value if it shows appropriate performances associated with a low cost. On the contrary, a product is considered to have bad value if it fails to meet performance targets and has a high cost. Value Engineering (VE), as proposed by Miles, considers value as a functional attribute of the product, thus it can be increased either by improving the product function or reducing its cost. The VE framework encompasses techniques in which the system’s output is optimized by crafting a mix of performances (or functions), looking at ways to improve the main function (what “does the job”); and costs (looking at eliminating or reducing supporting functions or unwanted functions by the customer).

An attempt to categorize different value definitions (Neap and Celik 1999) distinguishes between objective value (the value that buyers actually receive), subjective value (the value which buyers perceive that they receive), or even experiential value (the value buyers perceive as weighted psychologically by the salience of different dimensions—tangible or intangible—of value).

Shapiro and Jackson (1978), together with Forbis and Mehta (1981), conceptualize objective value in relative terms, as the maximum amount a customer should be willing to pay, assuming full information about the product and competitive offerings. Reuter (1986), Wind (1990) and Normann and Ramirez (1993) are among the pioneers to stress the notion of value-in-use, which highlight the importance of the relationship between the company and the customer, whose perception of value is not limited to the product performance (Ravald and Grönroos, 1996; Vandermerwe, 1996; Winkström, 1996; Woodruff and Gardial, 1996; Vargo and Lusch, 2004). The concept of value-in-use is later put into contrast with the concept of value-in-exchange, which “in essence concerns resources used as a value foundation which are aimed at facilitating customers' fulfillment of value-in-use” (Grönroos 2008). When an economist observes an exchange, two important value functions are revealed, which are those of the buyers and of the sellers. Just as the first group reveals what it costs them to give up the goods, the latter reveal what they are willing to pay for a certain amount of a good to satisfy their expressed and tacit needs.

Anderson et al. (1993) define value in business markets as the “perceived worth in monetary units of the set of economic, technical, service, and social benefits received by a customer firm in exchange for the price paid for a product offering, taking into consideration the available alternative suppliers offerings and prices.” Based on their experiences within the product development processes in Swedish and International companies, Lindstedt and Burenius (2006) further define customer value in terms of “perceived customer benefit” divided by the “use of customer resources”, the latter intended as money, time and effort.

Value may also be seen as a perceived benefit received relatively to the price (Monroe 1990), as an emotional bond established between a customer and a producer (Butz and Goldstein 1996). Zeithaml (1988) notices that perceived value is the quality the buyer gets for the price paid or what the buyer gets for what the buyer gives in the transaction. The term ‘get’ or benefit components of value include salient intrinsic and subjective attributes such as the feeling of touching or using the product, extrinsic attributes such as brand name, logos, charm, social status and perceived quality. Nagle and Holden (1994) similarly point out: “market value is determined not only by the product’s (actual) economic value, but also by the accuracy with which buyers perceive that value and by how much importance they place on getting the most for their money.”

Customer value is also related to past memories and is affected by group dynamics. Norman (2002) brings many examples to explain how customer value things or objects beyond the functional value they provide to them, for instance through the stories they tell or the memories they generate. Buyers may inaccurately

rately perceive value because they are unaware of the product or service's value or they are not persuaded that the product or service delivers the value promised by the provider. This sphere of customer value is referred to in some papers as Intangible Value (Daum 2002) or Emotional Value (Desmet et al. 2001), which act as an over layer upon the value that the products or services provide. Although conceptual models to assess intangible value exist (see: Steiner and Harmon 2009), the complexity of the subject is advocated to demand more research (Sullivan and McLean 2007).

In spite of being the center of attention, there is still relatively little knowledge in engineering design about what value is, what its characteristics are and how stakeholders determine it. In a conceptual development phase, the challenge is to understand how to develop solutions that deliver value in situations where customer expectations evolve and challenge the product and service definition.

Toward Value Driven Design

Within the overall context of product development, the engineering design process has drawn interest from academia and industry over the last 50 years, resulting in a number of systematic approaches from idea generation to industrialization (see: Hubka and Eder 1988, Pugh 1991, Pahl and Beitz 1996, Otto and Wood 2001, Ulrich and Eppinger 2008, Ullman 2009). Among others, Systems Engineering (SE) (Chestnut 1967), which focuses on how to design and manage complex engineering projects over their life cycles (ANSI/EIA-632) (INCOSE 2012), has evolved as the dominant framework for designing complex systems (Price et al. 2007). Requirements are at the core of the SE approach: they communicate, regulate and coordinate what has to be realized to satisfy customer needs, ensuring robustness and quality of the development process outcome. A design is considered satisfactory from a SE point of view only if requirements are met. Hence, the objective for the designer becomes to develop solutions as much as possible "requirements-compliant", and able to meet the threshold in terms of, for instance, performance, weight, specific fuel consumption or reliability.

SE has resulted in extraordinary achievements in shipbuilding, aerospace, automotive, urban infrastructure design and computer software (Honour 2004). However, it is also responsible for large overruns in both project cost and schedule, as described in well-documented examples. The recent Airbus A380 programme, for instance, suffered from an economic overrun of \$16 billion (approximately 50% of the total estimated cost of the project) and carried with it a two-year time delay for entry into service (Rothman 2011). Similarly, Boeing suffered from delays and an overrun cost with its B787 programme (Fotos 2009). Chevrolet (Achenbach 2009) and NASA (Valdes-Dapena 2009) have been brought up as additional examples of SE failures.

After reviewing these cases, Collopy and Hollingsworth (2011) revitalized the debate on the meaning of requirements when approaching the design of complex systems. The dichotomy between designing to performance requirements versus value was raised already by Herbert Simon (1969) in his essay entitled ‘The Science of Design’. Ideally, engineered systems should be optimized according to an objective function (e.g., value), but realistically this is often too hard, so that attributes would need to be “satisficed” (i.e., satisfied and sufficed), which amount to setting performance requirements.

Current SE standards are claimed not to address ‘value’ in much detail (Collopy and Hollingsworth 2011, Isaksson et al. 2013), mainly because VDD requires detailed attention to a wide range of parameters that are not merely related to the technical specifications of the solution. Collopy and Hollingsworth (2011) are among the firsts to propose Value Driven Design (VDD) as a way to cope with this problem. The VDD umbrella term, as defined by the AIAA Value Driven Design Program Committee (<http://www.vddi.org/vdd-home.htm>), gathers today several research groups in the USA and Europe. This body of knowledge is complemented by other initiatives, as described in the following sections.

Value as profitability for system operators

In the spirit of George Hazelrigg (1998) who stated: “Values tell engineers what you want. Requirements only tell them what you don’t want”, VDD is an improved design process that, in its classical formulation, utilizes value models to determine the value of their product designs as a single objective function. Such function, or “value model”, accepts a vector of attributes as its argument to assign a score (scalar) to rank a design. Since “profitability” is by far the most intuitive dimension to assess the value of a system (Soban et al. 2011), the “best” design is one that ultimately produces the best overall economic value (Castagne, Curran and Collopy 2009, Curran et al. 2010, Collopy and Hollingsworth 2011, Fanthorpe et al., 2011, Cheung et al. 2012).

Surplus Value or Net Present Value (NPV) scores are proposed as potential objectives for profit. They represent an unbiased metric of the ‘goodness’ of the final product (Collopy and Hollingsworth 2011) and relate both to the operating cost to be borne by the customers and their revenue. VDD further propagates the long-term profitability idea to the systems and sub-systems to enable optimum solution strategies to be instantiated in objective, repeatable, and transparent manner.

Value as system flexibility and robustness

For systems characterized by high cost, long lifecycles, high complexity, interdependencies with other systems and dynamic operational contexts, value is also determined by the ability to maintain or improve a function in presence of change.

During the early 2000's, a significant amount of research on system flexibility was produced at the Engineering Systems Division of the Massachusetts Institute of Technology (Joppin and Hastings 2003, Long et al. 2007). Within this group, Olivier de Weck et al. (2003) developed new methods for exploring a design tradespace using Generalized Information Network Analysis. Similarly, Ross et al. (2004) considered customer value embedded in the customer process context and utilises the concept of "ilities" to evaluate the system robustness under changing process conditions. Both de Weck et al. and Ross et al. employed a graphic form of optimization, called Tradespace exploration, in which designs are plotted against two orthogonal axes, utility and cost, to measure components of value by their position.

The Epoch framework later proposed by Ross and Rhodes (2008) allows the systematic creation of trade-space model(s) to quantify a range of "ilities", such as survivability, adaptability, flexibility, scalability, versatility, modifiability and robustness. Other methodologies did exist previously, such as Real options for flexibility (Saleh et al. 2003) but just for a few of these aforementioned criteria. Later, Brown et al. (2009) developed a Value-Centric Design Methodology (VCDM), which puts the emphasis on quantifying the value of flexibility and robustness. Nowadays, definitions and application of VCDM are closely aligned with VDD (O'Neill et al. 2010).

The notion of value is also connected with 'uncertainty'. In this field, Briceno and Mavris (2005) proposed a method to determine the value of design under market uncertainties by the use of game theory and NPV evaluation. Cardin et al. (2007) further elaborated on uncertainty, using Monte Carlo simulations and financial functions such as Return on Assets (ROA), NPV or Value At Risk and Gain (VARG) to help designers and managers of engineering systems in incorporating flexibility at an early design stage. Schindler et al. (2007) further proposed a methodology called "Systemics for Complex Organisational Systems' Design" (SCOD'S), which focuses on the integration of different aspect of stakeholders' demands, such as sustainable development, environmental issues, safety, hygiene, ethics or working conditions. Similarly, Petetin et al. (2010) have underlined the "value type" created by innovation in every stakeholder, considering six different type of value: social, environmental, image, knowledge, quality and economic.

Value as an intangible, experiential-based dimension

Steiner and Harmor (2009) proposed an extended model of customer value, adding a new layer: intangibles. Goods and services can be arrayed on a continuum of relative tangibility, with goods being more tangible and services being more intangible (Swartz et al. 1992). Intangibles are associated with knowledge and emotions, dimensions that cannot be experienced by the customer before using the product. Intangibles interact with the product and service layer to form a “value platform” from which total customer value is some combination of each layer of the total product. To translate these concepts in practice, techniques such as means-ends analysis, part-whole analysis and multi-attribute utility theory are introduced to understand customer values in depth and breadth (Zhang et al. 2013).

Similarly, Kowalkowski and Kindström (2009) propose a structured, three-tiered hierarchy of value criteria for PSS design. They distinguish between Product-based, Service-based and Relationship-based values. Product-based values include traditional product performances, quality, unit price, environmental impact and sustainability concepts (Goedkoop et al. 1999), Service-based values include operational costs, customization benefits and service consistency, while Relationship-based values include proactivity, trust, long-term commitment and shared norms and mind-sets. The latter are based on the idea that the supplier and the customer maintain a relationship over time (Vargo and Lusch 2004, Grönroos and Voima 2012).

Working with Value Driven Design

In its classical definition, VDD postulates that engineers, when making design choices, must select the “best” design, rather than selecting the one that is most likely to meet requirements (Hazelrigg 1998). Collopy and Hollingsworth (2011) explains VDD using a cyclical view of the design process. As shown in Figure 1, a design results from multiple passes at the design problem. As the first step, the design team picks a point in the design space at which to attempt a design. At the Design Variables step, it creates an outline of the design, which is elaborated into a detailed representation in the Definition arc. In the Analysis arc, engineers produce a second description of the design instance, in the form of a vector of attributes. While the design variables are defined to make sense to the design engineers, the attributes are defined to connect to the customer.

Fig. 1: The VDD cycle (Collopy and Hollingsworth 2011)

Collopy and Hollingsworth state that the Evaluate arc is what differentiates VDD from traditional Systems Engineering. This step is about determining whether the attributes meet requirements. If they do, the cycle is complete, otherwise, another round is attempted, or the team capitulates. Under VDD, the attributes are assessed with an objective function or value model, which gives a scalar score to any set of attributes. If the current configuration has a better score than any previous attempt, it is the preferred configuration to date. At this point, the design team can accept the configuration as their product, or try to produce an even better design by going around the cycle again.

The Evaluate step requires the development of a system value model. As explained in the previous section, such a model is often conceived as a long-term profitability model, whose two most important parts are representations of 1) how the customer makes revenue from the product and 2) how the product causes the customer to incur costs. For instance, the revenue that an aircraft can generate depends on the airline operations, which are directly linked to the aircraft product model. Thus, the aircraft product model provides the attributes needed for the system value model to run: aircraft payload, fuel burn, weight, reliability, number of engines, development cost, unit cost, maintenance cost, etc. In turn, the engine product model provides the engine attributes needed by the aircraft product model (Cheung et al. 2012).

A critical activity is to determine the connections between the engineering attributes of the product to the value model, which is the aircraft attributes that affect the revenue and the operating and manufacturing costs. By determining where the quantifiable links lie, it is possible to populate the combined model (composition function) with equations calculating aircraft attributes from given inputs. The next step is to derive local objective functions for each component from the system value model (surplus value).

An example from the aerospace sector

An illustration of how VDD principles can be applied to develop aircraft engine components has been provided by University of Southampton in collaboration with the aero-engine manufacturer Rolls-Royce plc. (Cheung et al. 2012). In this particular work two case studies have been considered: a) the effect of two continuous design variables, i.e. turbine entry temperature (TET) and overall pressure ratio (OPR), and b) the effect of a discrete variable, i.e. the material choice of the low pressure fan blade on the overall surplus value generated by the aero-engine operating for a certain amount of time in a fleet of aircraft.

The aero-engines perform better at higher temperatures. This has been the driving force in the aero-engine design since their inception in the 1940s and the TET of all aero-engines has been increasing with the help of better materials and new and more effective cooling methods. The first case study considers the effect of TET and OPR on the surplus value of an engine and how it can be used as a decision metric during conceptual design phase. The TET directly influences the weight, maintenance and manufacturing costs, emissions, and specific fuel consumption (SFC) of the final design (Cheung et al. 2012). Figure 2 shows the dependency of the surplus value of an aero-engine design on OPR and TET. The step change in surplus value in the TET axis is due to a sharp increase in engine efficiency, which yields improved stage lengths and better utilization of the aircraft, hence significantly increasing the revenue of the aircraft fleet.

Fig. 2: Sample result showing surplus value with respect to engine OPR and TET (Cheung et al., 2012)

When the chief design engineer along with a team of specialists, known as Integrated Project Team (IPT), are faced with a design choice on the material type of low pressure fan blades, they need consider a number of different engine attributes. This single choice between traditional titanium fan blades and new composite fan blades is by no means a simple decision. The whole team has to consider the effect of these design choices on performance, weight, cost, reliability, maintenance, and noise (Cheung et al. 2012). In order to make an informed decision, all of the positive and negative effects of these two design alternatives have to be assessed in an objective manner. For example, using composite fan blades may yield a lighter and more efficient aero-engine, but, on the other hand, this new and unproven technology may have detrimental effects on manufacturing and maintenance of the final design.

The surplus value of these two design alternatives can provide an objective decision support mechanism and the design team can choose the material that generates higher surplus value. Figure 3 shows the normalized results of this case study, which suggests that using carbon composites in the low-pressure fan blades may provide better surplus value in the context of a fleet of aircraft operating for an assumed period (Cheung et al. 2012).

Fig. 3: Normalized values of the surplus value of using conventional and carbon composite fan blades (Cheung et al. 2012)

Research initiatives

The American Institute of Aeronautics and Astronautics (AIAA), a program committee of government, industry and academic representatives (<http://www.aiaa.org/>), is a major promoter of VDD approaches in the United States. Within AIAA, the Value Driven Design Institute (VDDI) is the main body dedicated to scientific research of Systems Engineering applied to large complex systems. VDDI is currently focusing on the validation of VDD methodologies at large and small scale level. An ongoing initiative with the Georgia Institute of Technology aims at simulating an entire development program for a large aerospace system (Collopy and Poleacovski 2012), by means of agent-based simulations. At a smaller scale, the work is oriented toward understanding how to represent individual engineers, designers, managers, design teams, design tasks, the design product, and design methodologies, within the simulation model (Compton et al. 2012).

In parallel, the US Defense Advanced Research Projects Agency (<http://www.darpa.mil/>) works on a value-centric system design methodology, which incorporates value-driven architectural decision-making in complex system design. Four industry-led teams (Lockheed Martin Company, Northrop Grumman Corporation, Orbital Sciences Corporation and Boeing Company) are independently developing a Value-Centric Design Methodology (VCDM) tool to quantitatively assess the net value of fractionated spacecraft, relative to comparable monolithic spacecraft. All four tools use MATLAB as a “back-end” and employ discrete event simulations coupled with a Monte Carlo Analysis (MCA). In this spirit, researchers at MIT’s Systems Engineering Advancement research initiative (SEARI, <http://seari.mit.edu/>) continue the development of new value-driven methods to facilitate optimization tasks during the concept generation phase.

In Europe, the “Decision Environment for Complex Designs” (DECODE) project (<http://www.soton.ac.uk/~decode/>) is an EPSRC funded project, lead by the University of Southampton, which applies VDD principles to the design of an unmanned air vehicles (UAVs) with full autonomous control systems.

The “Flapless Air Vehicle Integration Research” (FLAVIIR) was an initiative funded jointly by BAE Systems and EPSRC between 2005 and 2010 with the intent to develop an operations simulation of a fleet of UAVs to evaluate technology options (Wood 2006). Meanwhile, a demonstration of how the profitability of commercial aircraft can be improved by using a value model for fuselage section design has been given by the Center of Excellence in Integrated Aircraft Technologies at Queen’s University of Belfast (Castagne et al. 2009), which is developing value-driven design strategies for aircraft structures.

The “Strategic Investment in Low-carbon Engine Technology” (SILOET) (Rolls-Royce 2009) is another initiative involving Rolls-Royce plc, BAE Systems and GKN, whose intent is to develop sophisticated life-cycle cost (LCC) and unit cost tools consistent with the VDD vision.

Recently, the EU FP7 “Collaborative and Robust Engineering Using Simulation Capability Enabling Next Design Optimisation” (CRESCENDO) project (<http://www.crescendo-fp7.eu/>) has investigated how to improve the requirements establishment process by using value as a main driver for aircraft and aero-engine preliminary design. The work has brought to the definition of innovative mechanisms to capture, model and understand customers’ and stakeholders’ needs and expectations (Isaksson et al. 2013), to incorporate the value drivers into preliminary design concept selection processes (Bertoni et al. 2013), and to visualize value in preliminary design studies evaluation (Bertoni et al. 2013).

Issues and Themes in VDD research

In its classical definition, VDD strongly focuses on design optimization. The application of VDD approaches in real working environments, together with recent research initiatives, have started to recognize the role of VDD as a mechanism to reinforce early stages design iterations, and to foster interactive relationships among customers, producers and suppliers. In this spirit, the following sections highlight areas of further research to promote the effective use of the VDD methodology as co-creation device while designing complex engineering systems.

VDD as a framework for co-creation

In the interpretation of Isaksson et al. (2013), VDD adopts an information-driven approach, which links customer expectations to the product engineering characteristics. In this perspective, VDD is thought as a framework for enabling quick what-if assessment loops to be executed at all levels of the supply chain in the very early stages of the design process, well before detailed requirements are made available by the aircraft manufacturer. Figure 4 considers a simplified aeronautical supply chain to show how VDD is positioned in relation to traditional Requirements Management. The underlying hypothesis is that VDD allows each manufacturer to reach a more advanced stage in the development of sub-systems and components compared to what happens when only requirements are made available.

Fig. 4: VDD vs. traditional Requirements Management (Isaksson et al 2013)

VDD provides to supply chain partners information that clarifies the context and underlying intent of each requirement. Without VDD, the lack of a holistic view and of a flexible approach to develop attractive solutions, might lead to sub-optimisation - suppliers have a tendency to follow their “normal specification” and make decisions in line with their own preferences - or even to project stagnation. Value is essentially the object around which both the discussion on solution strategies revolves and the multi-disciplinary design teams reach an agreement on the early system specifications and features.

Isaksson et al. (2013) further define the Value Creation Strategy (VCS) as the entity (or the document) that enables the sharing of preliminary design information among the parties in the supply chain. A VCS carries the description of a specific context: it includes a set of rank-weighted needs for the super-system, system and sub-systems, and that it is further detailed in value dimensions and value drivers. Rank-weighted needs, which emerge from the analysis of customer and stakeholder expectations and needs, are cascaded down to Value Dimensions and further detailed in several Value Drivers (VDs), which represent solution directions influencing the customer and end user perceived. Although less formalized and more volatile than the requirements description, these dimensions carry

contextual information that is neither formalized nor shared by the aircraft manufacturer with the collaborating partners.

Elaborating on Figure 4, Bertoni et al. (2011) propose a 6-dimensional framework (Figure 5) to guide the development of a list of VDs that provides a complete picture of lifecycle issues to be considered when performing a value analysis.

Fig. 5: Value dimensions and examples of value drivers for concept evaluation.

The framework looks firstly at the Operational Performances gains related to alternative designs. For instance, this dimension can relate to Value Drivers such as availability, maintainability and reliability. These are factors that have a direct impact on the value perceived by the airlines, and are eventually mirrored by the selling price of the product.

Also, what the customer is willing to pay for a 'solution' is determined by the ability of a system to deliver value where the customer value scales change (e.g.,

due to changing environmental and market conditions). Value robustness is captured by the *Ilities* dimension, a term borrowed from McManus et al. (2007).

Profitability in global markets also boils down to the ability of reducing production, testing, shipping and commercialization costs in front of the same level of value provision, hence a Profitability dimension encompassing these perspectives is considered.

The empirical study has also shown that, in complex supply networks, the ability of satisfying contractual requirements carries many values, both tangible (penalties of different kinds) and intangible (loss of trust between the collaborating partners). Requirements satisfaction is a critical dimension in the decision making process, hence the ability to achieve performance target is assessed in the value model. The framework further encompasses Risk as it aims at providing a feedback about the feasibility, knowledge gains, novelty, and maturity of alternative solutions proposed. Eventually, it considers those intangible dimensions related to the value perceived by the end users (e.g. passengers) or even by the customers and suppliers, such as brand acknowledgement, charm factor, social welfare, and environmental impact.

The assessment of VDs is traditionally conducted using monetary units, as they are proposed as the most convenient, practical, and universally understood metric for value regarding revenue-generating products (Collopy and Hollingsworth 2011, Cheung et al. 2012, Curran, 2010). However, when using VDD as an enabler for cross-company collaboration, a subjective definition of value seems to be more appropriate, as it might enhance communication between project management and designers (Soban et al. 2011). Quantitative monetary figures are built on knowledge with a low degree of confidence. Since VDs cannot be monetized in a meaningful way, the lack of trustworthiness on the data diminishes the potential use of the VDD methodology.

A preference toward using simple scalars to rank designs has clearly emerged from the study (Bertoni et al., 2013). Scalars enable direct comparisons of heterogeneous drivers, putting the focus not only on physical and functional architectures, but also on relationship-based aspects (Soban et al. 2011). In addition, more than in producing an absolute value score, a preference was expressed toward understanding how a concept is positioned against relevant benchmarks, to highlight if and how much a solution is better or worse than reference options. Two main references have been identified at this purpose: a product baseline (derived from historical data) and a target, which expresses a vision emerging from long-term forecasts (Bertoni et al., 2013).

Understanding the customer value scale

The use of VDD as framework for co-creation raises several issues related to how the relevant information for value modeling activities can be gathered, shared and interpreted by design teams.

VDD promotes gathering knowledge about the customer processes to determine, early on, if a product will be exposed to conditions that will affect its functions while in operation – and eventually affecting the profitability for the customer. The knowledge base from which the product specifications are drawn has to be extended to know more about the ultimate customer needs and to tailor the hardware for a successful functional life. For instance, knowing how pilots operate the aircraft during takeoff and landing in specific situations, may suggest completely rethinking the architecture of the aero-engine to make it more profitable under a lifecycle perspective. In an extreme scenario, common plastics might even be preferred for some components, instead of using exotic composite materials. Plastic is cheap, it allows introducing expensive features at reasonable cost, and parts can simply be replaced at each inspection, thus changing the cost structure.

VDD also insists on knowledge about issues that could affect the long-term value provision, such as maintenance, monitoring, training, remanufacturing, ecological constraints or regulations, even disposal and recycling. For products such as an aero-engine, which can be kept in service for as much as 30-40 years, knowing how monitoring systems and maintenance practices are going to evolve is vital to understand how to optimize the provision of a function and be profitable under changing environmental conditions.

Companies, however, seem to have little knowledge about how their products are used in practice in real environments (Kauppinen et al. 2009). Such “downstream” knowledge (i.e. from later lifecycle phases) is dispersed across functions and organizations, and is even less formalized and agreed than technical product information - which is, it is mainly tacit (Polanyi 1983). This is accompanied by a lack of informal knowledge exchange among individuals partaking development efforts. As shown by Larsson et al. (2010), people in these teams belong to different functions – i.e., they are cross-functional (Dube and Paré 2004) - do not normally have a previous history of working together, there are no ‘shared assumptions’ of how collaborative work may proceed and the inevitable flux of team members over time makes even more difficult to share experiences, know-how and receive feedback.

In the last decade the software industry has been at the forefront of the implementation of social technologies in design (Di Gangi and Wasko 2009). Nowadays, manufacturers in the aerospace (Warwick 2010) and automotive (Awazu et al. 2009, Mamgai and Sanjog 2009) sectors are currently taking the first steps in this direction (Bughin 2009), exploring how a more bottom-up approach to knowledge sharing can support the development of more innovative value propositions.

In this context, the authors have investigated the role of social technologies to reveal the customers value scale, which is, to gather relevant knowledge to set up a value study and populate a value model.

Previous studies (Larsson et al. 2010, Bertoni and Larsson 2011) have already pointed toward exploiting Web 2.0 mechanisms to increase the engineering designers' awareness about what is "hot" at the customer side. The objective is to leverage engineers' social ties within and outside the organization, facilitating the team in aggregating, filtering and validating knowledge from the front line to better comprehend the customer value scale. Furthermore, they support engineers in recognizing the right context in which the customer needs originate and evolve, while spotlighting how the perception the value delivered can change when the environmental conditions evolve (Bertoni et al. 2012).

The study has shown that weblogs are often used as a platform for early feedback from external stakeholders and employees, allowing them to engage in discussions (Payne 2008, Jim 2009) on value-related matters. Weblogs lower the threshold for presenting ideas, findings and personal experiences to a large audience, and enable people with similar interest to rate, comment or ask for elucidations. Wikis are more suited for collaboratively growing ideas for future products and to define and refine best practices from the different lifecycle phases, facilitating idea and experience sharing among the stakeholders.

Forums could allow engineers to raise critical value-related issues with the other partners in the network, managing heavily moderated topical conversations over a prolonged period (Mayfield 2009), scaling up internal conversations to get feedback from experts in various domains and disciplines. The strength of microblogs is, instead, on their capability to spread innovative ideas, quotes, or links that may allow others to give real-time and focused feedback on technical or service matters. Tagging practices may facilitate the discovery of relevant knowledge outside the product development boundaries, making easier to locate and fetch information tagged in the same way from different sources and that refer to the same value dimensions and drivers. Eventually, social bookmarking may enable global engineering teams to search and find experts on specific topics, or people with similar interests in the projects, based on informal browsing of bookmark collections.

The most evident benefit of social technologies for VDD lies in the possibility of reducing the time and effort to identify knowledge owners from the front line, to browse their inputs and to increase the awareness of the multi-functional issues regarding a given topic. Eventually engineers and designers in a preliminary phase may benefit from an increased awareness on people that can provide relevant value knowledge for a study and, consequently, from the learning opportunity offered by their continuous feedback.

Assessing the maturity of value-related knowledge

For radically new technologies and designs, VDD is about creating predictive models built on qualitative data, assumptions and forecasts, because historical series of data is missing. This opens up several concerns about the reliability and accuracy of the outcomes of the value simulation and of value trade-offs.

Some of the emerging questions are: What is the level of completeness of the information in the value model? Is any information missing or ambiguous? What assumptions have been made? Are there needs for further developments of knowledge assets to contribute more clearly to the objective? Is there any reason to complement (or perhaps challenge) the formal documentation? How much trust can you put in the output of a value assessment activity, based on the information and knowledge it is based on?

In these situations, there is a degree of uncertainty that needs to be handled, perhaps not by directly focusing on reducing the uncertainty, but rather by assisting the decision makers in achieving a better understanding of what those uncertainties, ambiguities, and assumptions actually involve. It is particularly important to have pointers that can indicate the level to which people may trust the material entering in the value assessment activity, supporting decision makers in challenging value-related assumptions.

The concept of Knowledge Maturity (Johansson et al. 2011) is seen as a necessary complementary activity to value assessment. Knowledge Maturity provides in this perspective a practical decision support tool for increasing decision makers' awareness of the knowledge base and for supporting cross-boundary discussions on the perceived maturity of available knowledge.

Table 1: Contextualized scales for maturity assessment (Johansson et al. 2011)

		Input	Method	Experience/Expertise
5	Excellent	Very good quality of input data with assessment by customer as well as several independent sources.	Develop support system for risk assessment regarding future volume and prices.	Long-verified experience and expertise within the area of concern.
4	Good			
3	Acceptable	Market survey based solely on data from customers.	Systematic modus operandi with qualitative risk assessment regarding prices and volume.	Proven experience and competence within the area of concern.
2	Dubious			
1	Inferior	Data from customers and independent sources are missing.	No evaluation of external data.	The person doing the work is inexperienced (first-time).

The knowledge maturity model computes the state of readiness of a knowledge asset using a narrative scale over three dimensions: input, method (tool), and ex-

pertise (experience) on a scale from 1 to 5 (Table 1). Johansson et al. (2011) rank Level 5 as an Excellent knowledge maturity level, meaning that content and rationale have been tested and proven and reflect a known confidence, that the procedure to produce the content and rationale reflects an approach where tried out methods are used, where workers continually reflect and improve and where lessons learned are recorded. Level 4 is defined as Good and level 3 as Acceptable. Knowledge maturity is Acceptable when the content and rationale are more standardized, there is a greater extent of detailing and definition and the procedure to produce the content and rationale is more stable (compared to previous levels) with an element of and repeatability. Level 2 is Dubious and level 1 is Inferior. The knowledge maturity level 1 means that the content and rationale is characterized by instability (e.g. poor/no understanding of knowledge base) and the procedure to generate the content and rationale is dependent on individuals and formalized methods are non-existent.

The knowledge maturity concept enables an assessment of input data, of the tools to refine or develop the input into an output, and of the individuals contributing to the work. Furthermore it allows teams at different locations to have a shared artifact around which they can identify and discuss issues of concern, visualize the current status of the knowledge base, and negotiate a shared understanding of the advantages and drawbacks with the available knowledge base.

Accessing partners' value models

Since coopetition, i.e., 'collaborating with the enemy', is becoming increasingly common in the domain of global product development, being able to handle the rapid transformations in and out of a consortium of risk sharing partners is critical (Larsson et al. 2010). Each partner company in the network needs to know, in terms of knowledge sharing, what they can bring into the partnership and what they can take from it. In terms of value modeling activities, the mutual exchange of knowledge and models to perform value analysis tends to be reduced to a minimum to avoid the risk of being drained of core know-how.

A major theme for VDD research becomes then how to enhance enterprise collaboration capabilities to enable a conjunct management of requirements and value information in complex supply chains.

A feasible approach in this context is to treat the relevant models for value analysis as black boxes, i.e. sharing their location while exposing only the inputs of the models and allowing just the outputs of the calculation, without exposing its underlying mechanism or logic. The concept of black boxes imply that an object is viewed only in terms of its inputs, outputs and transfer characteristics without any knowledge of its internal workings, that is, its implementation is "opaque". In this context, web services can offer a feasible solution by allowing the client (a company that is part of the virtual enterprise) to access a value model (implemented by

another company). During this interaction the following processes take place: 1) the server provides a well-defined interface – a Web Services Description Language (WSDL) document – of the value model to the client, 2) the client processes the WSDL document and provides the inputs required by the value model to the server, and 3) the server calculates the value and returns it to the client. In this overall process the knowledge on the internal workings of the value model is not exposed to the client.

The authors have extensively used Vanguard Studio (<http://www.vanguardsw.com/>), a commercial software package dedicated to graphical and hierarchical model development, to implement such a black box concept in the optimization of pylon-engine-nacelle assemblies (Bettebghor et al. 2013). An important feature of Vanguard Studio is the automatic web deployment capability, which allows model developers to publish their models on the server, so that they can be viewed and run by other users through a standard browser. Vanguard Studio enables the creation of different models related to important company data. These models can be automatically converted into a web service, so that they can be used by a higher-level model just calling them through their associated Uniform Resource Locator (URL). As soon as a model is published, a WSDL document describing the inputs and outputs of the model along with its URL is created. The models are not stored in any central location; rather they are stored within the proprietary companies and can be accessed from other clients requiring a minimal amount programming effort. If needed, designers can also access and run the models interactively. Obviously for security purposes the overall process is protected by usernames and passwords, and access can be limited to certain network numbers.

Models implemented by different companies can interact in a common platform, simply sharing variable values but not sharing the structures from which this variable came from. This can be used to protect the privacy of relevant data, preventing other companies to extract information from the value models.

Communicating and visualizing value contribution

A single engineer does not design systems, components, or even parts (except perhaps simple fasteners and brackets). Instead, teams of engineers, often from multiple disciplines work together to design these artefacts. Engineering has therefore become a fundamentally social activity, and the phenomena of social psychology, such as group dynamics and sense making, are now considered as fundamental concepts (Collopy, 2012). For a program involving the design of a complex system to be successful, communication must occur at all levels of the design, and during the time of the entire design cycle. Engineers must communicate both within their sub-systems, across to other sub-systems at the same tier, and up and down the tiers. Program managers and leaders need to communicate

amongst themselves as well as with their design teams, and with stakeholders. Therefore, engineering information must be presented to stakeholders in such a way as to enhance their confidence in the results.

Information and knowledge visualisation have been recognised as key factors to leverage the way value-related information is used in conjunction with requirements during early concept selection activities. Creating an environment where engineers and designers can visually link ‘value’ to product components is a necessary step to enable more value-oriented decisions in design (Collopy 2012). Visualization plays the role of a boundary object (Carlile 2002), supporting decision makers in synthesizing and discussing the outcomes of value studies and reframing their understanding of what the future functional product will be.

However, the integration of innovative information visualization approaches in daily work practices is a labor-intensive and risky process (Sedlmair et al. 2011). Large companies require upfront authorization to deploy new software or tools in their working environment, for both functionality and security reasons. Furthermore, experts are often accustomed to and effective with the existing tools and methods, and the integration of a new solution may break the chain of analysis processes (Sedlmair et al. 2011).

Hara et al. (2009) promotes the use of CAD/PLM tools for lifecycle information visualization, as a way to limit users’ reluctance against new systems. In spite of the shortcomings in conveying usage, manufacturing and service information (Hannah et al. 2012), the recent market trends show that the scope of CAD/PLM is extending to support a wider range of analysis and data, from different fields (Srinivasan 2011). Recent releases embed modules and functions aiming at capturing customer needs and technical requirements, defining system architectures, modeling and validating systems behavior, and managing embedded software. CAD models are popular not only because they are easily shareable over the Internet, increasing communication between customers and suppliers, but also because they represent a good trade-off between perception of product representation and frequency of use, in comparison with hand-made sketches, scale models, prototypes, mock-ups, virtual reality and rapid prototyping (Engelbrektsson and Söderman 2004).

Hence, 3D CAD models might represent a suitable means to support visualization of value-related information in the early stages of design. Within the CAD product model description, colors have emerged as one of the key cues for value representation, mainly because colors precede the processing of other attributes (Karayanidis and Michie 1997) and facilitate associative processing (McNab et al. 2009). Color-coded 3D CAD models allow condensing the outputs of the value analysis in a unique representation, closely linking value to the object (feature, part or assembly) manipulated by the designer. Also, they highlight areas where modifications and redesigns are necessary to render a higher value contribution.

Application examples of this idea include an aero-engine intermediate compressor case (Bertoni et al. 2013) (Figure 6). The study exploits Siemens Teamcenter (<http://www.plm.automation.siemens.com/>) visualization capabilities

to automate the color coding of 3D CAD models emerging from the results of a value model calculation.

Fig. 6: Color-coded visualization of the value associated to the different parts of an aero-engine intermediate compressor case for a given value driver (Bertoni et al., 2013).

Conclusions

Within the domain of product development, and even more in the realm of SE, value assessment practices were a curiosity in the 1990's, while nowadays they seem to have become a standard feature of many aerospace programs. With product design and development becoming an even more collaborative activity, involving many individuals from a large variety of suppliers and sub-contractors, the concept of 'value' becomes appealing for manufacturers to elaborate a concise, overarching cross-system requirement specifications list, providing a summary of the most important requirements for a project.

Requirements alone have shown to provide insufficient insight into the original intent and context of a design, increasing the risk of delay, rework and sub-optimal solutions. Hence VDD methodologies are emerging as enablers for fostering co-creation activities across the supply chain, avoiding falling in the trap of focusing only on the nearest customer and targeting local optimal solutions, rather than on those dimensions that add value from a more system-level perspective.

Value provides a means to formalise such contextual information in a more structured form, taking relevant information out of the list and dispatching them to concerned sub-suppliers. This increases designers' awareness of the consequences of their choices during the design synthesis stage, when critical design decisions are made.

However, although a plethora of approaches for VDD have been described, with the majority focused on the economic aspects of value, very few real-life examples can be observed, and most of the approaches remain only at a conceptual level.

In the authors' experience, the adoption of VDD is still very minor, for different reasons. On an overarching level, researchers still have to identify and detail robust methodologies to capture, consolidate and prioritize needs and expectations, to condense them into value dimensions and drivers, and to use the latter in conjunction with requirements to guide design trade-offs dealing with multiple levels of customers.

The value models themselves have to evolve to encompass a wider range of dimensions, such as customer and end user perceptions and intangibles such as brand loyalty, to cope with the ambiguities in the knowledge base that make economic simulations not completely reliable. Not only value is difficult to quantify. Also, the perception of 'value' changes, sometime unexpectedly, over time. Unfortunately, current methods offer a limited support for decisions concerning the selection of design concepts optimized using a 'static' usage scenario in contrast to high latent value solutions that can adapt to changing needs and environmental conditions.

Improvements in the communication and the visualization of value across functions and companies are requested from many stakeholders. In preliminary design, this could enhance understanding and participation of stakeholders who have the necessary knowledge on the later product lifecycle, and that can contribute in enabling more value-conscious decisions.

Eventually, the development of small-scale examples how VDD works in practice is crucial to promote discussion on the topic and to trigger interest toward the experimentation of larger scale and robust prototypes in complex development projects.

A deep cultural shift will likely accompany the introduction and implementation of VDD. Nowadays, design and development activities are challenged by a company culture that encourages working with structured information only. The qualitative nature of the value analysis, and the underlying uncertainties in its knowledge base, is the main obstacle for its widespread adoption in product development activities. Engineers and designers have to become more acquainted to work with qualitative inputs and have to be prepared in dealing with ambiguities in a better way of what happens today in many product development environments.

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