Chapter 8
Industrial Systems

8.1 Smart Manufacturing

8.1.1 Industry 4.0

Industry 4.0 is a vision of integrated industry implemented by leveraging computing, software, and internet technologies. The label 4.0 refers to the vision of a fourth industrial revolution (Schwab 2016).

The 4.0 strategy emphasizes cooperation between industry and science to promote closer links between knowledge and skills. The reports of the industry 4.0 working groups, describe the using of Internet of Things technologies, communications, and web services in manufacturing. They create networks incorporating the entire manufacturing process that convert factories into smart factories (Zuehlke 2008; Kagermann et al. 2013). Linkages include smart machines, and production facilities that feature end-to-end integration, including logistic, production, marketing, and service. Industry 4.0 is projected to create closer cooperation between industry partners, suppliers and customers, and between employees, providing new opportunities for mutual benefit (Lee et al. 2015; Hermann et al. 2016; Hwang 2016).

The vision of industry 4.0 is significantly higher productivity, efficiency, and self-managing production processes where people, machines, equipment, logistics systems, and work-in-process components communicate and cooperate with each other directly.

A major goal is the application of mass production efficiencies to achieve make-to-order manufacturing of quantity one by leveraging embedded processing and communications. Production and logistics processes are integrated across company boundaries, creating a real-time lean manufacturing ecosystem that is more efficient and flexible. This facilitates smart value-creation chains that include all of the life-cycle phases of the product from the initial product idea, development, production, use, and maintenance to recycling.

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Networking companies in the supply chain make it possible to optimize individual production steps and the entire value chain. For example, comprehensive real-time information enables companies to react during production to the availability of certain raw materials based on price, quality, and other factors for optimal efficiency. External linkages enable production processes to be controlled across company boundaries to save resources and energy.

The fabrication of physical or chemical objects is revolutionized by emerging materials science. Engineers may design and build from the molecular level, optimizing features and creating new materials, radically improving quality and reducing waste.

Devices and products are already appearing based on computationally engineered materials that literally did not exist a few years ago: novel metal alloys, graphene instead of silicon transistors and meta-materials that possess properties not possible in nature.

This era of new materials will be economically significant when combined with 3D printing, also known as direct-digital manufacturing-literally printing parts and devices using computational power, lasers and basic powdered metals and plastics. Already emerging are printed parts for high-value applications like patient-specific implants for hip joints or teeth, or lighter and stronger aircraft parts.

The digitization of industry is forecasted to foster new business models and present great opportunities for small-and medium-size enterprises. For example, to build low-volume metal parts, companies build virtual 3D models and use direct metal laser sintering, an additive process similar to 3D printing that deposits metal powder layers melted by laser, to create parts. These parts are fully dense metal with specified mechanical properties. Significantly, the 3D process can produce complex geometries that traditional machining processes are not capable of creating.

Conventional assembly manufacturing lines are synchronous, with predefined workflows based on production work orders running in enterprise business systems. Production steps are centrally communicated to each manufacturing station synchronized with the assembly line. In contrast, industry 4.0 is based on asynchronous manufacturing, with components in the production flow using self-identification technology to inform each machine and operator what needs to be done to produce the customized end product at each step of the production process. The use of new flexible machines that adapt to the requirements for the part being made is another capability of industry 4.0. This achieves a highly flexible, lean and agile production process enabling a variety of different products to be produced in the same production facility. Mass customization allows the production of small lots due to the ability to rapidly configure machines to adapt to customer-supplied specifications and additive manufacturing.

Industry 4.0 systems capture a wide range of data that can be used to improve performance and productivity with the application of analytics. Analytics are used in a number of ways, including real-time predictive maintenance, which helps manufacturing companies avoid interruption of production by unplanned machine failures on the factory floor-directly improving asset utilization. Another application

Table 8.1 Digital manufacturing initiatives

Country	Year	Name
Australia	2013	Next wave of manufacturing
Belgium	2013	Made different
Canada	2015	Smart manufacturing, industrie 4.0
China	2015	Made in China 2025
Denmark	2012	Made
France	2015	Industrie du futur
Germany	2011	Industrie 4.0
India	2014	Make in India
Japan	2015	Industrial value chain initiative
Netherlands	2014	Smart industry
South Korea	2015	Manufacturing industry innovation
Sweden	2014	Produktion 2030
UK	2014	High value manufacturing
USA	2012	Advanced manufacturing partnership

of analytics is optimization of production operations, improving productivity and energy efficiency.

Industry 4.0 initiative is influencing thinking throughout the world, which in turn influences other initiatives and cooperative efforts.

The term Industrie 4.0 originated in Germany, but the concepts are in harmony with worldwide initiatives, including Advanced Manufacturing Partnership, Industrial Internet, smart manufacturing, and smart factories.

Table 8.1 shows the name of similar digital manufacturing initiative in different countries.

8.1.2 Smart Manufacturing Leadership Coalition

The Smart Manufacturing Leadership Coalition (SMLC) was founded in the USA to overcome the costs and risks associated with the commercialization of smart manufacturing systems. The SMLC has not explicitly embraced Industry 4.0, but its vision and mission embrace many of similar concepts (Bryner 2012; Davis et al. 2012). The SMLC mission is to lead the industrial sector transformation into a networked, information-driven environment in which an open, smart manufacturing platform supports real-time, high-value applications for manufacturers. The mission is to optimize production systems and value chains, and radically improve sustainability, productivity, innovation, and customer service. SMLC intends to develop a cloud-based, open architecture manufacturing infrastructure and marketplace through the collaboration of manufacturing thought across industry, academia, consortia, and government.

SMLC goals include integrating plant-level systems and data, accelerating the development and deployment of reusable applications, providing an open and secure infrastructure accessible and affordable to all, and embracing evolving business needs and new market opportunities.

Greater manufacturing complexity, dynamics-based economics and radically different performance objectives requires the pervasive application of networked information-based technologies that transform a facilities focus to knowledge-embedded facilities, a reactive operational approach to one that is predictive, incident response to incident prevention, compliance to performance, and vertical decision making to local decision-making with global impact. Existing assets need to become globally competitive while the installed base of equipment runs its investment life cycle. Operating costs need to be lowered. Performance will need to be responsive to multi-faceted objectives. Advanced manufacturing and advanced networked information and computation technology will become significant.

The manufacturing workforce with advanced training and skills is the key competitive advantage as dynamic management and operation of demand-driven product profiles increase and as innovation and faster time-to-market for new products becomes a key economic driver. Small, medium and large manufacturers will depend on training and skills and the manufacturing workforce will distribute throughout the supply chain, advanced technology suppliers, innovation and start-up companies. Workforce training will no longer be about vertical factory operations but about dynamic interaction, innovation, rapid product changes, and new products to market all with sustainable operations spread across a widely distributed base of small and large companies. Not only will workforce training need to address a dramatically distributed manufacturing approach but also the technologies that support it. Smart manufacturing envisions the enterprise that integrates the intelligence of the customer, its partners and the public. It responds as a coordinated, performance-oriented enterprise, minimizing energy and material usage while maximizing environmental sustainability, health and safety and economic competitiveness. Business, operations, management, workforce and manufacturing process transformations are in response to new ways of reasoning about the manufacturing process. Smart manufacturing has been defined as the dramatically intensified application of manufacturing intelligence throughout the manufacturing and supply chain enterprise to both lead and respond to a dramatic and fundamental business transformation toward demand-dynamic economics, performance-based enterprises, demand-driven supply chain services and broad-based workforce involvement and innovation. This intensification of manufacturing intelligence comprises of the real-time understanding, reasoning, planning and management of all aspects of the enterprise manufacturing process and is facilitated by the pervasive use of advanced sensor-based data analytics, modeling, and simulation. SMLC is committed to a comprehensive vision in which technology and the business, operating and workforce models are transformed in concert to achieve a steep change in manufacturing productivity with respect to value add product economics. The deployment of smart manufacturing involves complex on-the-ground detail, difficult applications of technical and operational approaches, difficult business models, the management of significant risk, and the need for research and development in new technologies, business models and organization engineering. The SMLC comes with a set of goals that no one company can accomplish alone:

- Integrate the intelligence of the customer, partner and public throughout the manufacturing supply chain
- Develop the collective capacity to respond as coordinated factory and supply chain enterprises
- Perform against new cross factory and supply chain key performance indicators that are radically different from traditional output/input metrics
- Increase the base of workforce innovation
- Increase productivity and quality by lowering the cost of IT infrastructure, sensing and the pervasive deployment of modeling and simulation
- Build equivalent capability across small, medium and large enterprises together
- Build a workforce that is trained in performance oriented decision making
- Define the technology research and development that is needed to achieve the full vision

8.1.3 Reference Architectures

The Industrial Internet is an internet of things, machines, computers and people enabling intelligent industrial operations using advanced data analytics for transformational business outcomes, and the Industrial Internet Consortium (IIC) is devoted making the Industrial Internet a reality.

The reference architecture addresses the Industrial Internet problems by providing common and consistent definitions in the system of interest, decompositions, and design patterns, and provides a common terminology to discuss the specification of implementations so that options may be compared.

Industry 4.0 and related initiatives recognize that efficiently building self-managing production processes requires open software and communications standards that allow sensors, controllers, people, machines, equipment, logistics systems, and products to communicate and cooperate with each other directly. Future automation systems must adopt open source interoperability software application and communication standards similar to those that exist for computers, the internet, and cell phones.

Industry 4.0 demonstrations acknowledge this by leveraging existing standards, including the ISA-88 batch standards, ISA-95 enterprise-control systems integration standards, IEC 6-1131-3, and others.

The harmonization of standards worldwide took another step forward when providers of the Platform Industry 4.0 and the Industrial Internet Consortium (IIC) met to explore the potential alignment of their two architecture efforts-respectively, the Reference Architecture Model for Industry 4.0 (RAMI4.0) and the Industrial Internet Reference Architecture (IIRA).

The OPC Foundation and Object Management Group (OMG) initiated a collaborative strategy for technical interoperability that encompasses the OPC Unified Architecture (OPC UA) and the OMG Data Distribution Service (DDS) standard.

These significant cooperative efforts recognize that manufacturing has worldwide interdependencies requiring common standards and interoperability (OMG 2008).

The Reference Architectural Model Industry 4.0, RAMI 4.0, consists of a three-dimensional coordinate system that describes all crucial aspects of industry 4.0. In this way, complex interrelations can be broken down into smaller and simpler clusters.

The Hierarchy Levels axis is based on the levels from IEC 62264, the international standards series for enterprise IT and control systems.

These hierarchy levels represent the different functionalities within factories or facilities.

In order to represent the industry 4.0 environment, these functionalities have been expanded to include work pieces, labeled Product, and the connection to the Internet of Things and Services, labeled Connected World.

The Life Cycle and Value Stream axis represents the life cycle of facilities and products, based on IEC 62890 for life-cycle management. Furthermore, a distinction is made between types and instances. A type becomes an instance when design and prototyping have been completed and the actual product is being manufactured.

RAMI 4.0 combine the basic elements of industry 4.0 in a three-dimensional layer model. Based on this framework, industry 4.0 technologies can be classified and further developed.

The Layers axis show six layers on the vertical axis and serve to describe the decomposition of a machine into its properties structured layer by layer, that is, the virtual mapping of a machine. Such representations originate from information and communication technology, where properties of complex systems are commonly broken down into layers.

These six layers are:

- Asset: representation of reality, such as a technical subject,
- Integration: providing computer processing information of assets,
- Communication: standardization of communication, using a unified data format,
- Information: software environment for event pre- processing,
- Functional: modeling environment for services that support business processes,
- Business: business models and the resulting business process

Within these three axes, all crucial aspects of industry 4.0 can be mapped, allowing objects such as machines to be classified according to the model.

Highly flexible industry 4.0 concepts can thus be described and implemented using RAMI 4.0. The reference architectural model allows for step-by step migration from the present industrial stage into the world of industry 4.0.

RAMI 4.0 integrate different user perspectives and provide a common understanding of industry 4.0 technologies. With RAMI 4.0, requirements of sectors—from manufacturing automation and mechanical engineering or chemical process engineering—can be addressed in standardization committees. Thus, RAMI 4.0 provide a common understanding for standards and use cases.

RAMI 4.0 can be regarded as a 3D map of industry 4.0 solutions. It provides an orientation for plotting the requirements of sectors together with national and international standards in order to define and further develop industry 4.0.

8.1.4 Generic Smart Grid Architecture Model

The generic Smart Grid Architecture Model, SGAM, can act as a reference designation system in order to describe smart grid technical use cases as well as business cases.

The approach used in SGAM for reference designation proved its value, and it is necessary to follow basic guidelines for successful adoption of derived models for other domains (Fang et al. 2012; Uslar and Engel 2015).

One of the key challenges resulting from the Smart Grid vision is to handle complexity in the new distributed systems landscape. The Smart Grid, being a true system-of-systems is a prime example for the increasing complexity that emerges in any distributed system.

SGAM provides the means to express various domain-specific viewpoints on architecture models by the concepts of so called Domains, Zones and Layers.

Figure 8.1 shows the Layers for the original SGAM model for reference designation of standards.

The elements of the polytopic architecture from Fig. 8.1 have been identified as follows:

- S-Component
- K1-Communication
- K2-Information
- K3-Function

Fig. 8.1 Layers for SGAM

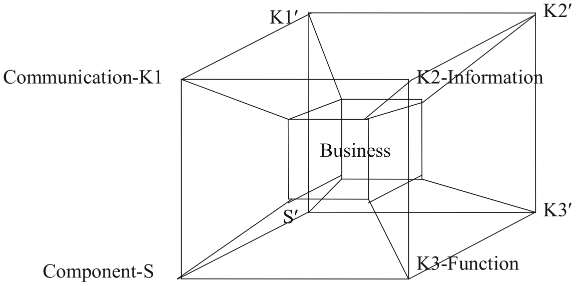
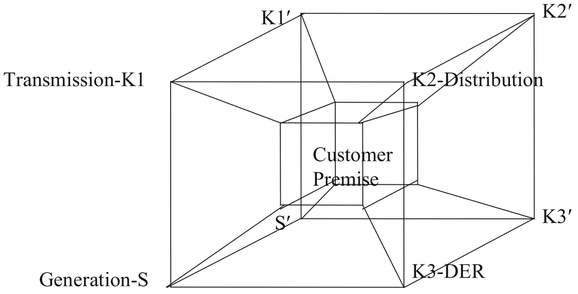


Fig. 8.2 Domains for SGAM



- Self-Business

Business is identified as the Self of this polytope.

The Domains of SGAM regard the energy conversion chain and include: generation (conventional and renewable bulk generation capacities), transmission (infrastructure and organization for the transport of electricity), distribution (infrastructure and organization for the distribution of electricity), DER (distributed energy resources connected to the distribution grid) and customer premises (both end users and producers of electricity, including industrial, commercial, and home facilities as well as generation).

Figure 8.2 shows the Domains for the original SGAM.

The elements of the polytopic architecture are identified as follows:

- S-Generation
- K1-Transmission
- K2-Distribution
- K3-DER
- Self-Customer Premises

Customer Premises are identified as the Self of this polytope.

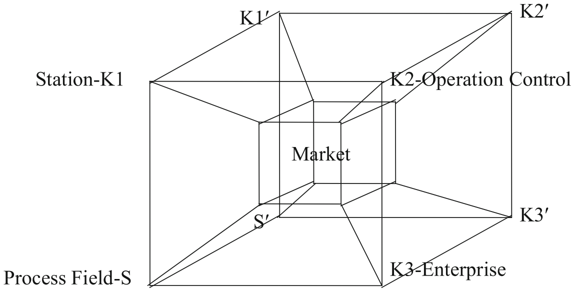
The hierarchy of power system management from the automation perspective is reflected within the SGAM by the following Zones: process (physical, chemical, biological or spatial transformations of energy and the physical equipment directly involved), field (equipment to protect, control and monitor the process of the power system), station (areal aggregation level for field level), operation control (power system control operation in the respective domain), enterprise (commercial and organizational processes, services and infrastructures for enterprises), and market (market operations possible along the energy conversion chain).

Figure 8.3 shows the Zones for the original SGAM.

The elements of the polytopic architecture are identified as follows:

- S-Process Field
- K1-Station
- K2-Operation Control
- K3-Enterprise
- Self-Market

Fig. 8.3 Zones for SGAM



Market is identified as the Self of this polytope.

SGAM may be represented using multi-level polytopes. Layers covers coarser granularity that Domains and these coarser granularity than Zones.

Reference architectures based on SGAM as generic reference architecture has been presented by Uslar and Engel (2015).

The Smart City Infrastructure Architecture Model (SCIAM) is one particular new derivative from the original SGAM model. The roadmap for Smart Cities is based on the original model of the SGAM. Instead of the business layer, an action layer was proposed.

As for Domains and Zones, new axes have been developed.

The Zones cover a mostly hierarchical way of structuring for physical locations. Market, Enterprise, Operation, Station and Field as well as Process, forms the Zones axis. This list can be considered a natural ordered list. In addition to this, the Domains consist of Supply/Waste Management, Water/Waste Water, Mobility and transport, Healthcare and Civil Security, Energy, Buildings as well as Industry.

The Electric Mobility Architecture Model (EMAM) is a particular architecture which is currently being developed in the context of the IT for electric vehicles programs.

It is a need for a consolidated use case collection and then deriving actors and technical requirements from them which will provide the basis of changing the granularity of the individual axis aspects. Re-using the SGAM in terms of modeling electric mobility is required.

The concept of the Home and Building Architecture Model (HBAM) has been developed to come up with a Standardization Roadmap on Smart Home and Building.

The Layers have been renamed to application, function, data model, interface and protocol and finally component.

The Zones axis contains the electronic health, building automation, physical security, consumer electronics and energy domain. Just like with the SCIAM more domains than one are addressed, but this time in the Zones area. The Domain axis has been structured with the lanes of devices, interfaces, control, accesses and data exchange.

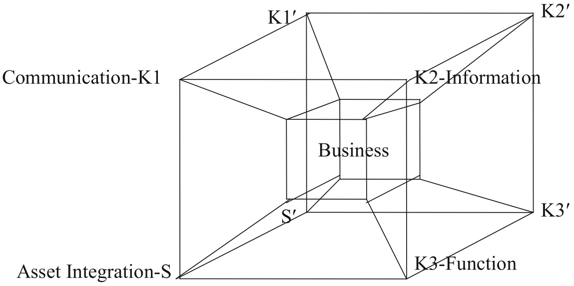


Fig. 8.4 Layers for RAMI 4.0

The Reference Architecture Model for Industry 4.0 (RAMI 4.0) is an advanced derivative of SGAM (Uslar and Engel 2015). In addition to business, function, information, communication and asset representing component, a new layer called integration was introduced. The Domain and Zone axis are not custom taxonomies but are based on the IEC 62890 value stream chain or the IEC 62264/61512 hierarchical levels, respectively.

Figure 8.4 shows the Layers for RAMI 4.0.

The elements of the polytopic architecture are identified as follows:

- S-Asset Integration
- K1-Communication
- K2-Information
- K3-Function
- Self-Business

Business is identified as the Self of this polytope.

For this polytope presentation the asset and integration are considered as a single layer.

Figure 8.5 shows the Levels for RAMI 4.0.

The elements of the polytopic architecture from Fig. 8.5 are identified as follows:

- S-Product Field
- K1-Control Station
- K2-Work Unit

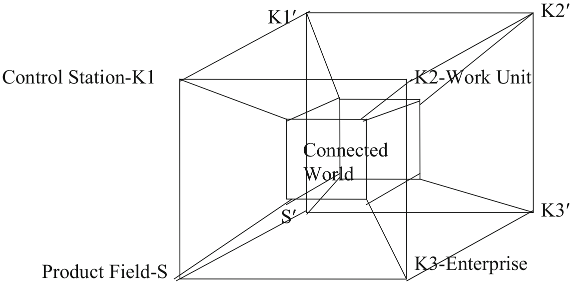


Fig. 8.5 Levels for RAMI 4.0

- K3-Enterprise
- Self-Connected World

Connected world is identified as the Self of this polytope.

The model harmonizes different user perspectives on the overall topic and provides a common understanding of the relations between individual components for industry 4.0 solutions. Different industrial branches like automation, engineering and chemical process engineering have a common view on the overall systems landscape.

8.2 Systems Development

8.2.1 V-Model

V-model is a general reference model for complex systems design and validation. A large number of different types of the V-models are used in industry (Estefan 2007; Strang and Anderl 2014).

V-model is suitable for presenting specification phases and associated validation test phases. The individual validation tests—acceptance tests, system tests and integration tests—are executed alongside the corresponding specification documents, user requirements and system specifications or technical specifications.

The V-model always offers a simplified and easily understandable presentation of the approach when validating is required between the specification and test phases.

The V-model was given its name from the presentation of the letter V in which the left-hand part represents the specification and design phases while the right-hand part the validation and test phases. The left side of the V-model represents the decomposition that is the refinement of design, while the right side describes the composition that is assembly or integration tasks.

Horizontal lines are drawn between the left- and right-hand parts of V-model. This illustrates that a dependency and a dialogue exists between the specification input, left-hand part, and the validation test phase output, right-hand part.

Figure 8.6 outlines the individual phases of the V-model.

The elements of the associated polytopic architecture from Fig. 8.6 are identified as follows:

- S-Detail Validation
- K1-Integration Validation
- K2-System Validation
- K3-User Acceptance Validation

Implementing polytope project starts from the direct sequence $S \rightarrow K1 \rightarrow K2 \rightarrow K3$ and complete this by the reverse sequence: $K3' \rightarrow K2' \rightarrow K1' \rightarrow S'$ (Iordache 2012, 2013).

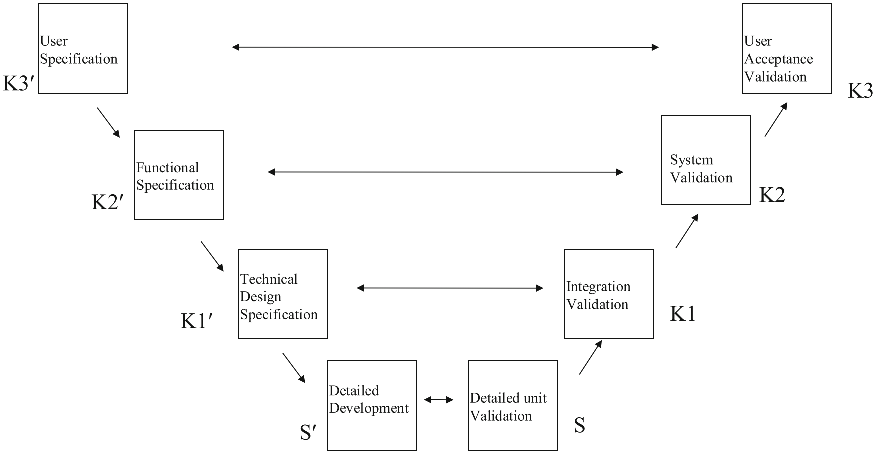


Fig. 8.6 V-model

The right-hand side corresponds to the direct sequence while the left-hand side corresponds to the reverse sequence.

One could identify the levels in the reverse sequence shown in Fig. 8.6 as:

- K3′-User Specification
- K2′-Functional Specification
- K1′-Technical Design Specification
- S′-Detailed Development.

Figure 8.7 shows the polytope for V-model presented in Fig. 8.6.

The user requirement specification document contains either the process or the function-based requirements of the users and operators or the system owner.

The development and writing of requirements may vary in the context of the functional or process related basis. It is recommendable to write requirements on a process-based interpretation. In the functional specification the user requirements

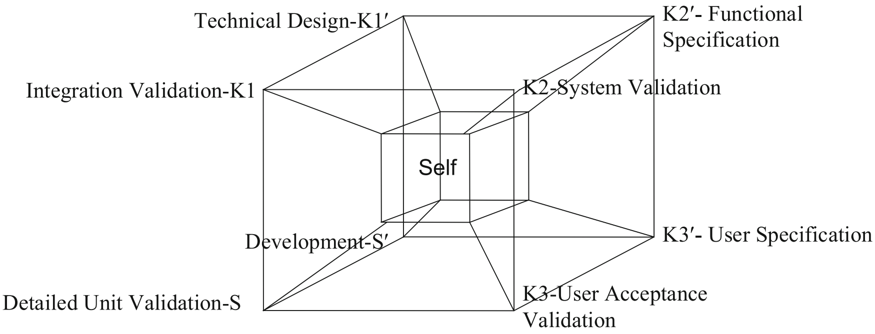


Fig. 8.7 Polytope for V-model

are transformed further in functional terms for the purpose of the system implementation.

The technical specification design is an explanation for the programmer or the developer implementing the system function.

In program development, the technical specification is translated into an executable program. The technical design can also contain the specification of the required hardware and may comprise several parts. The unit validation test is related to the testing phase of the logical software modules or units.

The integration validation test is used for verifying the fulfillment of the technical specifications and the correct interactions between the different units or modules.

In the system validation the system is checked against the system specifications.

In the acceptance requirements the system is checked against the user requirements.

Currently, the development of mechatronic systems is often based on the V-model for the development of mechatronic systems according to guidelines which was derived from the original V-model for software development (Gausemeier and Möhringer 2003).

A case study, the template based V-model design analyzed by Kazenbach et al. (2007) is presented in Fig. 8.8.

The design process using templates follows a V-model as presented in Fig. 8.8.

The V-model starts from layout definition consisting of the basic structure, for instance body-in-white of a car (Kazenbach et al. 2007). It is then refined to provide details through the instantiation of templates, first assembly templates, then part templates and finally feature templates for the detailing phase. Then the various parts are assembled or integrated to reach the final design. During the V-model implementation, study templates are applied at several levels to evaluate the design.

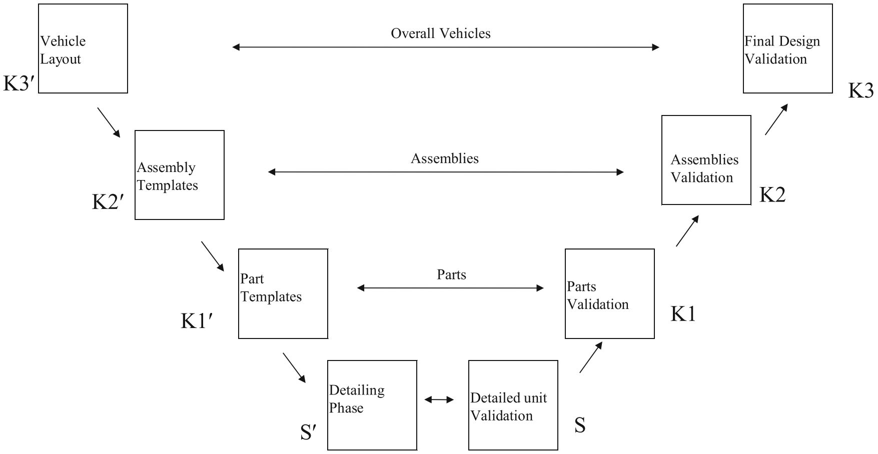


Fig. 8.8 Template based V-model

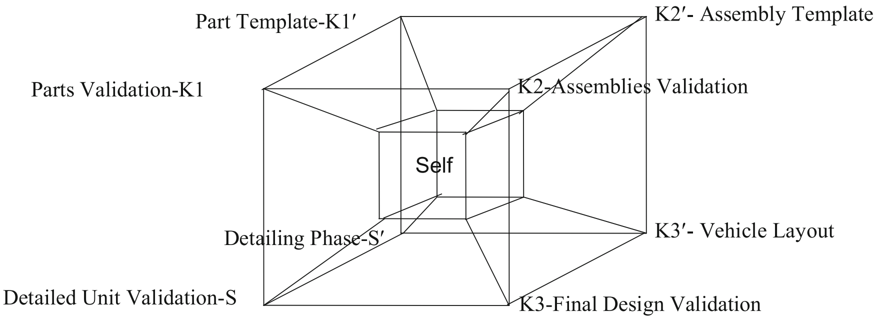


Fig. 8.9 Polytope for template based V-model

Templates allow standardizing the design concepts and share them between several products. A study of the human factors regarding template use has been conducted. The objective was to evaluate the human factor in the adoption of templates aiming at the standardization of the process and to improve how templates are designed in order to facilitate its acceptance.

Figure 8.9 shows the polytope for template based V-model.

The elements of the polytopic architecture shown in Fig. 8.9 are identified as follows:

- S-Detailed Unit Validation
- K1-Parts Validation
- K2-Assemblies Validation
- K3-Final Design Validation

Implementing polytope project starts from the direct sequence S → K1 → K2 → K3 and complete this by the reverse sequence: K3′ → K2′ → K1′ → S′. One could identify the levels in the reverse sequence for instance:

- K3′-Vehicle Layout
- K2′-Assembly Template
- K1′-Part Template
- S′-Detailing Phase

8.2.2 Polytope Projects for Continuous Engineering

Continuous engineering represents a new approach to systems engineering. It retains the overall systems focus, levels of abstraction, and core activities that form the basis of systems engineering but puts a new spin on how the activities are conducted. It also adds some fresh ingredients to pull in market and operational knowledge from outside traditional processes and suggests ways to exploit strategic assets, such as engineering data and reusable code.

Figure 8.10 shows the V-model for continuous engineering approach.

In continuous engineering, the V no longer represents a sequential series of steps, as did the traditional V-model for systems engineering. Instead, it represents activities that are conducted iteratively and, to the greatest extent possible, in parallel, as needed throughout the product development process, relationships between activities, and linkages among engineering, operational, and market data.

So, for instance, requirements (left side of the V) are updated as changing or refined user needs are discovered from system verification or new operational data becomes available (right side of the V). Updated requirements in turn trigger changes in design, development, and testing. The middle of the V represents the ongoing interactions between left-side-of V activities and right-side-of V activities. This augments the relationships already spelled out by the shape of the V itself - requirements are related to designing, design is related to development, and so on, with the base of the V representing the implementation and embodiment of the requirements. The focus needs to be on actual running systems that may be virtual models, so teams can focus on executing system scenarios to manage risk and validation assumptions throughout the project life cycle.

Figure 8.11 shows the polytope project for continuous engineering approach.

The elements of the polytopic architecture are identified as follows:

- S-Detailed Validation
- K1-System Test
- K2-System Validation
- K3-Operation Maintenance Validation.

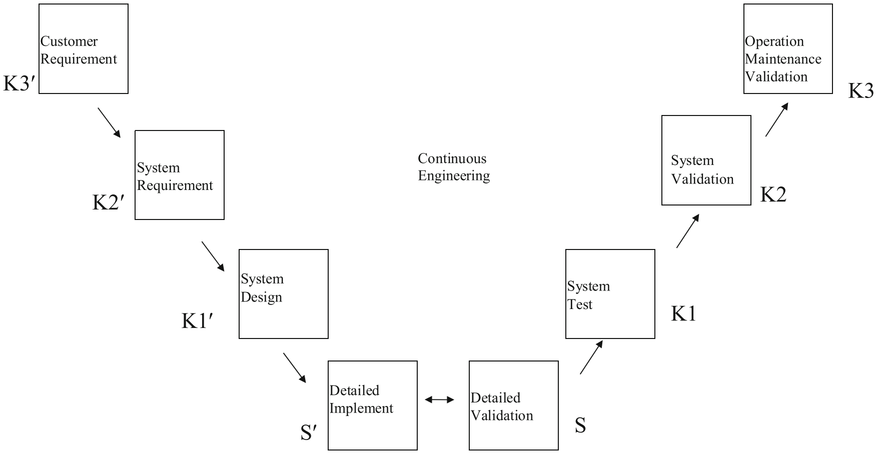


Fig. 8.10 Continuous engineering V-model

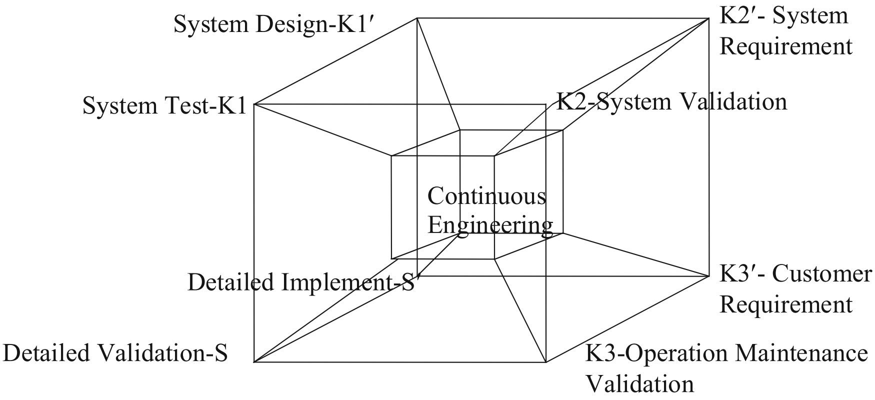


Fig. 8.11 Polytope for continuous engineering

Implementing polytope project starts from the direct sequence S → K1 → K2 → K3 and complete this by the reverse sequence: K3′ → K2′ → K1′ → S′.

One could identify the levels in the reverse sequence for instance:

- K3′-Customer Requirement
- K2′-System Requirement
- K1′-System Design
- S′-Detailed Implement
- Self-Continuous Engineering

Continuous engineering from the middle of V-model is identified as the Self of this polytope project.

The basic levels are S, K1, K2 and K3 represented on the front face of the outer cube and S′, K1′, K2′ and K3′ represented on the back face of the outer cube of the polytope.

The dialogue between the two faces of the outer cube is mediated by the inner cube identified as the Self.

Figures 8.10 and 8.11 illustrate the importance of data relationships in an engineering context. Best practices in continuous engineering include sharing data across engineering disciplines, reusing design elements whenever possible, and incorporating market and operational data into product development activities.

Continuous engineering builds on the foundation of systems engineering practices by persistently applying engineering tools, methods, and techniques to address change and close gaps between current design plans and last requirements.

8.2.3 Logic and Hopf Algebras

The left side of the V-model represents the decomposition that is the refinement of design, while the right side describes the composition that is assembly or integration tasks. This suggests making use of Hopf algebras for V-model implementations (Sweedler 1969; Joni and Rota 1979; Blasiak 2010, Appendix B)

Combinatorial Hopf algebras emerged as the appropriate instrument in the study of composition and decomposition processes. The product or multiplication describes the assembly while the coproduct or comultiplication describes the disassembly.

A general problem for industrial systems development is that of specifying the utilized mathematical and logical models. The challenge is to describe the logic and the Hopf algebra behind the V-model or polytope project implementation. For instance, it would be of interest to identify the logic and the Hopf algebra behind the V-model design process at Daimler-AG (Katzenbach et al. 2007). The coproduct would describe the road from Vehicle Layout to Detailed Design while the product would describe the road from Detail Validation to Final Design Validation. The actual designs are a subset of what is logically possible.

Blute (1996) introduced Hopf algebras as a unifying framework for modeling several variants of multiplicative linear logic. By varying the Hopf algebra we are able to model the conventional commutative, non-commutative and cyclic linear logic. It is important to have a generic mathematical tool for modeling all these variants as this will allow direct comparison of the various theories and models. The structure of the variant we are modeling is reflected in the structure we require of the Hopf algebra. The particular Hopf algebra may be selected and will control the degree of symmetry of the model.

Benson (1989) introduced bialgebras as foundations for distributed and concurrent computation. Blute and Scott (1998) studied a Hopf algebra that is useful to describe concurrent processing. The key idea is the shuffle.

Consider a process containing many steps ordered by the logic of production.

Given two sequences a = x1x2 … xn and b = y1y2 … ym a shuffle is a permutation of the list x1x2, …, xn, y1, y2, …, ym such that the internal order of a and b is maintained in the result. Shuffle describes the switch between the sequences, a and b.

Let SH(a, b) denotes the set of all shuffles of a and b. The interleaving process naturally carries the structure of Hopf algebra.

It is an example of incidence Hopf algebra (Schmitt 1994).

Let X be a set and X* the free monoid generated by X. We denote the words that is the strings in X* by w, w′. The product is:

$$w \otimes w' \to w * w' = \sum_{u \in Sh(w,w')} u \tag{8.1}$$

Here Sh (w, w′) denotes the set of shuffled words of length |w| + |w′| obtained from w and w′. The coproduct is:

$$\Delta(w) = \sum_{w1w2=w} w1 \otimes w2 \tag{8.2}$$

Note that in the equation w1w2 = w we are using the original monoid multiplication of X*.

There exists also an antipode (Blute and Scott 1996).

Differential linear logic as introduced by Ehrhard and Regnier (2006) extends linear logic with an inference rule which is a version of differentiation. This may be correlated to decomposition task, that is, the refinement of design.

The corresponding structures called differential categories were studied by Blute et al. (2006, 2009). There is a natural transformation, called the deriving transform which models the differential inference rule. The relation with Faà di Bruno Hopf algebra is of interest for such studies (Figueroa et al. 2005).

The logical synthetic structure of integration was less studied than the differential logic.

It is an ongoing project to develop dual notions of integral linear logic and integral categories (Blute et al. 2010). Rota-Baxter Hopf algebras may be a source of inspiration for integral linear logic theory. Rota-Baxter algebras are associative Hopf algebras with an endomorphism which satisfies an abstraction of the integration by parts formula (Guo 2009). This algebra is appropriate for the study of compositions, that is, assembly or integration tasks.

Facing complexity is not only about differentiation bat also about integration and coordination.

The dual differential and integral linear logic may offer an answer to higher complexity problems as for instance modeling self-orientation for autonomous systems (Bartheye and Chaudron 2015).

References

Bartheye, O., Chaudron, L.: Algebraic models of the self-orientation concept for autonomous systems. In: 2015 AAAI Spring Symposium Series, pp. 14–21 (2015)

Benson, D.B.: Bialgebras: some foundations for distributed and concurrent computation. Fundam. Informaticae **12**, 427–486 (1989)

Blasiak, P.: Combinatorial route to algebra: the art of composition & decomposition. Discrete Math. Theor. Comput. Sci. **12**(2), 381–400 (2010)

Blute, R.: Hopf Algebas and linear logic. Math. Struct. Comput. Sci. **6**, 189–217 (1996)

Blute, R., Cockett J.R.B., Seely R.A.G.: Differential categories. Math. Struct. Comput. Sci. **16**, 1049–1083 (2006)

Blute, R., Cockett, J.R.B., Seely, R.A.G.: Cartesian differential categories. Theor. Appl. Categories **22**, 622–672 (2009)

Blute, R., Ehrhard, T., Tasson, C.: A convenient differential category. arXiv preprint arXiv:1006.3140 (2010)

Blute, R., Scott, P.: The shuffle Hopf algebra and noncommutative full completeness. J. Symbolic Logic **63**, 1413–1435 (1998)

Bryner, M.: Smart manufacturing: the next revolution. Chem. Eng. Prog. **108**(10), 4–12 (2012)

Davis, J., Edgar, T.F., Porter, J., Bernaden, J., Sarli, M.: Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Comp. Chem. Eng. **47**, 134–144 (2012)

Ehrhard, T., Regnier, L.: Differential interaction nets. Theoret. Comput. Sci. **364**(2), 166–195 (2006)

Estefan, J.A.: Survey of model-based systems engineering (MBSE) methodologies. Incose MBSE Focus Group. **25**(8) (2007)

Fang, X., Misra, S., Xue, G., Yang, D.: Smart grid, the new and improved power grid: a survey. IEEE Commun. Surv. Tutorials **14**(4), 944–980 (2012)

Figueroa, H., Gracia-Bondia, J.M., Varilly, J.C.: Faà di Bruno Hopf algebras. arXiv preprint math/0508337 (2005)

Gausemeier, J., Möhringer, S.: New guideline VDI 2206—a flexible procedure model for the design of mechatronic systems. In: Norell, M. (ed.), Proceedings of the 14th International Conference on Engineering Design (ICED), Stockholm (2003)

Guo, L.: What is a Rota-Baxter algebra. Notices of the AMS, **56**(11) (2009)

Hermann, M., Pentek, T., Otto, B.: Design principles for industrie 4.0 scenarios. In: 49th Hawaii International Conference on System Sciences (HICSS) IEEE, pp. 3928–3937 (2016)

Hwang, J.S.: The fourth industrial revolution (industry 4.0): Intelligent manufacturing. SMT (surface mount technology) Magazine, 10–15 (2016)

Iordache, O.: Self-Evolvable Systems. Machine Learning in Social Media. Springer, Berlin (2012)

Iordache, O.: Polytope Projects. Taylor & Francis CRC Press, Boca Raton (2013)

Joni, S.A., Rota, G.C.: Coalgebras and bialgebras in combinatorics. Stud. Appl. Math. **61**(2), 93–139 (1979)

Kagermann, H., Wahlster, W., Helbig, J. (eds.): Recommendations for Implementing the Strategic Initiative industrie 4.0: Final Report of the Industrie 4.0 Working Group (2013)

Katzenbach, A., Bergholz., W., Rolinger, A.: Knowledge-based design—an integrated approach, the future of product development. In: Krause, F.L. (ed.), Proceedings of the 17th CIRP Design Conference, pp. 13–22 (2007)

Lee, J., Bagheri, B., Kao, H.A.: A cyber-physical systems architecture for industry 4.0-based manufacturing systems. Manufact. Lett. **31**, 3, 18–23 (2015)

OMG.: Object management group, software & systems process engineering meta-model specification 2.0 (2008)

Schmitt, W.R.: Incidence Hopf algebras. J. Pure Appl. Algebra **96**(3), 299–330 (1994)

Schwab, K.: The Fourth Industrial Revolution. World Economic Forum, Geneva (2016)

Strang, D., Anderl, R.: Assembly process driven component data model in cyber-physical production systems. In: World Congress on Engineering and Computer Science, vol. **2**, pp. 22–24, (2014)

Sweedler, M.E.: Hopf Algebras, Mathematics Lecture Note Series. W. A. Benjamin Inc, New York (1969)

Uslar, M., Engel, D.: Towards generic domain reference designation: how to learn from smart grid interoperability. In: Poster Proceedings of DACH Energy Informatics 2015, 1–12 (2015)

Zuehlke, D.: Smart factory–from vision to reality in factory technologies. IFAC Proc. **41**(2), 14101–14108 (2008)