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High-performance benchmarking of manufacturing processes with object-based modeling

Xing Zhou, Holger Kohl,

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Xing Zhou and Holger Kohl
Corporate Management Division, Fraunhofer Institute for Production Systems and Construction Engineering IPK, Berlin, Germany

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Abstract

Purpose – The purpose of this paper is to guide companies in conducting benchmarking studies of their manufacturing processes by viewing across industries, locations and products. In particular, the proposed framework can help corporate decision makers in terms of production footprint and site location studies. The level of benchmarking performance can be measured by evaluating defined benchmarking evaluation profiles.

Design/methodology/approach – This paper develops a tool to operationalize value-added manufacturing processes for benchmarking evaluations. In this context, an object-oriented database structure has been developed for the business areas such as product development, manufacturing and assembly. This paper focuses on manufacturing processes. Furthermore, a framework for applying high-performance benchmarking has been developed and applied in a case study.

Findings – This paper shows that object class-oriented modeling approach can be applied to manufacturing processes. The higher the degree of independence in terms of locations, industry sectors and products, the more powerful thus a higher performance of benchmarking is achieved. The performance level of benchmarking has been defined by proving and demonstrating higher and lower performance levels. The high-performance benchmarking tool has been successfully applied to a production footprint case study.

Originality/value – This paper takes up the superiority of process benchmarking that has been the focus of numerous research papers on benchmarking techniques in the past. The potential of process benchmarking has been enhanced and operationalized as a tool. A classification logic for benchmarking evaluation profiles has been developed and integrated in the overall tool set. The model helps decision makers to configure their benchmarking studies tailored to their strategic entrepreneurial questions and to guide them to achieve a higher benchmarking performance level.

Keywords Manufacturing, Industrial processes, Integrated enterprise modelling, Object class hierarchies, Process benchmarking, Process modelling

Paper type Research paper

1. Introduction

Companies are continuously striving for higher performance to secure their competitive advantage. This can often be enforced by looking beyond their own perimeters. Complex and strategic questions require tools to support corporate decision processes in their early stages. The objective of this work is to develop a method that can be applied for benchmarking evaluations of value-added processes in the manufacturing industry. As evaluation intuitively starts by comparing the developed tool is based on benchmarking techniques. Consequently, the operationalization of value-added manufacturing processes is required to enable this kind of comparability. Their benchmarking range should not be limited to locations, industry sectors, processes or products. Looking back into the benchmarking technique history, this research refers to Camp's (1989) position that best practice business processes can be either identified among direct product competitors, among functional industry leaders or they can be generic processes themselves. Generic processes enable process benchmarking independently of the industry sectors. Process benchmarking primarily investigates the underlying success factors according to Kohl (2007) and its perspective beyond the own industry allows for a higher benchmarking demanding level (Töpfer, 1997). Examples of process benchmarking are customer service

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improvement in banking through benchmarking with the service of Singapore Airlines (Kärlof and Östblom, 1995), or the benchmarking between the assembly processes of a chocolate manufacturer and the printed circuit board mounting process from the semiconductor industry (Mertins and Kohl, 2009). Also in this period, Hewitt et al. (1996) note that the benchmarking evolution has moved from single function focus toward process benchmarking as well as cross-functional, cross-sectoral and value-oriented benchmarking. The literature has mainly focused on the superiority of process benchmarking referring to business processes, while the focus of this work is on industrial value-added processes. As support services along the life cycle of the product are gaining importance to fulfill customers' requirement (Asjad *et al.*, 2012) they are also considered as supporting processes for the industrial value-added processes. Benchmarking can help to detect suitable or innovative ways to enhance supportability independent of the underlying physical product or the existing branches.

In the author's view, process-benchmarking approaches could be further developed in the light of the increased availability of production factors across locations and current technological advances in processing large amount of data. Referencing to the higher level of benchmarking being achieved through process benchmarking as stated by Töpfer (1997), this study outlines a concept of measuring the performance level of benchmarking. The framework enables the user to increase its benchmarking performance level. In the model, the performance level of benchmarking is defined by the degree of independence from industry sectors, products, locations and even processes. Consequently, high-performance benchmarking leads us to identify superior production processes and to study their underlying success factors.

For identifying superior processes in the manufacturing environment they, first have to be made comparable. Key requirement is operationalization through standardization which is realized by means of standardized process elements (Kohl, 2007). A method to operationalize industrial value-added processes has been developed in order to enable process modeling based on an object class-oriented approach.

2. Operationalizing industrial value-added processes

From the modeling perspective, value-added processes are key as production strategies are derived from industrial value-added processes. Value-added processes are referred to any production processes within the manufacturing industry. In order to benchmark production processes across industry sectors and locations a tool has been developed to operationalize them through normalization. The modeling concept for any value-added process requires a defined process modeling tool that will enable benchmarking. The modeling tool is derived from the process model depicted in Figure 1 which comprises four perspectives including the value-added process itself. The remaining three perspectives are product, resources and

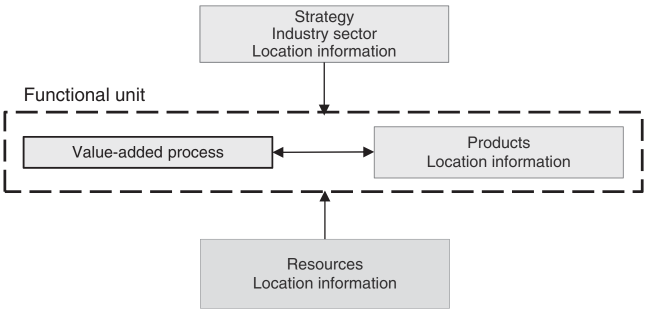


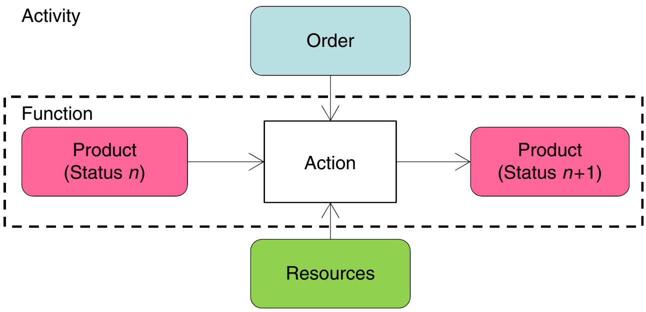
Figure 1.
Process model for value-added processes

the industry sector together with corporate strategy. The inherent process is independent from the product. Both processes and products form a functional unit. This functional unit of the value-added process and the product is further independent from industry sector and strategy. The strategy is the base to which the processes are aligned to. This is brought by the overall corporate strategy which includes both competitive and internationalization strategies. Furthermore, value-added processes are independent of their locations. Location characteristics are only related to the perspectives product, resources and strategy/sector. This location-independent value-added process analysis also corresponds to the benchmarking principle that best practice processes can be found worldwide. Finally, this model enables us to autonomously focus on the distinct value-added process irrespective of any influencing factors which are considered in the other perspectives product, resources and sector/strategy. In order to purely focus on the inherent value-added process all these factors have been decoupled from it.

Besides this process model a generic benchmarking database structure has been developed that structures certain modeling objects. The aim is to build a full-scale generic structure of objects, which can be selectively used to model various value-added processes that are going to be benchmarked. There are different methods for business process modeling in the literature (Aguilar-Savén, 2004; Becker *et al.*, 2000). The method applied refers to the Integrated Enterprise Modeling (*Integrierte Unternehmensmodellierung*) developed at the Fraunhofer Institute for Production Systems and Design Technology IPK (Süssenguth, 1991) since it is a proven tool for business process modeling and for process benchmarking (Kohl, 2007) and has several transfer benefits. The method is based on object-oriented enterprise modeling. In this work, this rationale of business process benchmarking has been transferred to the modeling of industrial value-added processes. The Integrated Enterprise Modeling follows the modeling logic of activities. The process serves as a nucleus in each manufacturing environment. Based on the object-oriented concept of Integrated Enterprise Modeling it integrates both processes (functions) and process information (data). This philosophy of object-oriented programming considers data and functions *en bloc* (Süssenguth, 1991). The relationship between functions and objects is named "Generic Activity Model." A hierarchy of the object classes exists and all objects classes are described by characteristics (Spur *et al.*, 1993). Objects are defined and describing characteristics are assigned to them. The benchmarking is then carried out based on these describing characteristics.

In order to map the activities of a production company the Integrated Enterprise Modeling defines three generic object classes which are "product," "order" and "resource." All activities can be related to one of these three generic object classes. Thus, any activities in manufacturing of products can be described by the "Generic Activity Model." The center is the action causing an activity. Enhancing the action by input and output objects leads to the function. An activity is formed when the function will be further enhanced by resources and order (Schwermer, 1997).

The Generic Activity Model (Figure 2) has been adapted to the process model (Figure 1) in order to model value-added processes. For full portability, an analogous approach between the Generic Activity Model of the Integrated Enterprise Model and the process model has been followed. This is derived using the concept and the components of the Integrated Enterprise Model. The functional unit, composed of the value-added process and input and output products, corresponds to the function consisting of action and products in the Integrated Enterprise Model. This functional unit of value-added process and product is defined as the value-added function. Resources are primarily defined as personnel and tools and equipment. Materials are assigned to the object class products. They include raw materials, supplies, components and processing and finishing products (VDI 2815). Resources, which have a specific location factor, help to perform and execute the value-added function. Resources are evaluated along the dimensions' performance, costs and quality. Thus, resources are the key



Source: Süssenguth (1991)

Figure 2.
Generic Activity Model of Integrated Enterprise Modeling

evaluation parameter of value-added functions. As mentioned above, the value-added function is also decoupled from any location restrictions. In fact, value-added functions can be compared independently of their location. Likewise, value-added processes can be compared independently of their input and output products.

The object class order initiates the value-added function and includes information on sector and strategy. Both activate the value-added function. In summary, the Generic Activity Model of the Integrated Enterprise Model has successfully been adapted to the process model displayed in Figures 1 and 3.

In the next step, benchmarking databases has been designed for each business area product development, manufacturing and assembly. Each database constitutes of object, function classes and their corresponding characteristics. Characteristics describe object classes that are hierarchically structured.

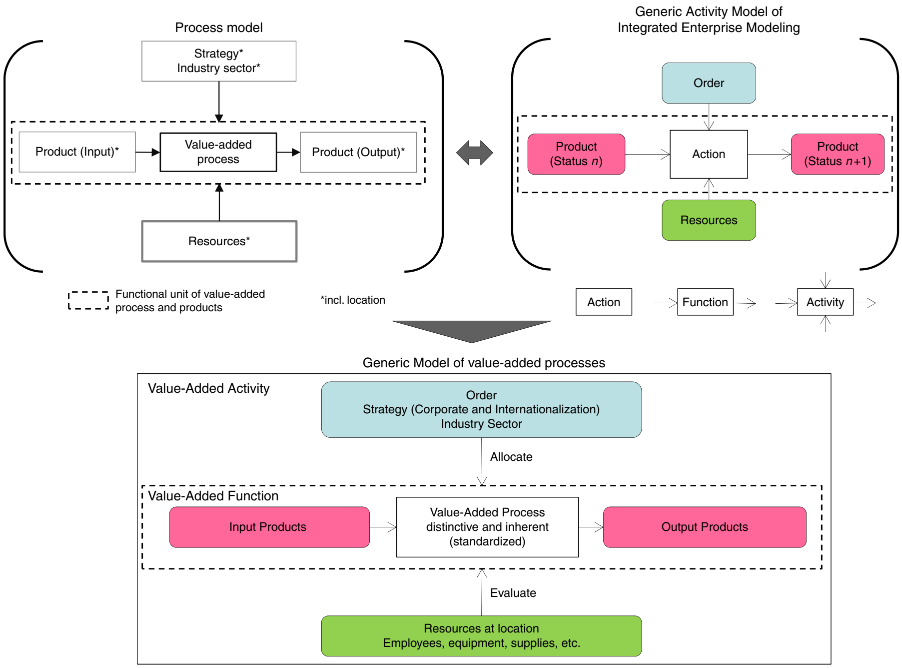


Figure 3.
Generic model of value-added processes through adoption of Integrated Enterprise Modeling

In this publication, the focus is only on the database for the business area "manufacturing." Object and function as well as characteristics classes represent the population of all objects and functions needed to model any manufacturing value-added processes. They are all normalized to a common standard. It covers any physical manufacturing processes for the production of products with geometrically defined bodies according to the German Industry for Standardization (DIN 8580: 2003 09). The Generic Activity Model for manufacturing processes is shown in Figure 4.

The activity is defined by the core manufacturing process. Depending on the manufacturing process, the input products can be formless (e.g. foundry) or already geometrically defined, solid bodies (e.g. semi-finished products). Output products are principally declared as products with geometrically defined solids.

Function and product object class structures have been developed. Only the first level of process objects is shown in this paper that are oriented to the systematic of manufacturing processes standardized by the German Institute for Standardization (DIN 8580).

The population of object and function classes enables the modeling of various manufacturing processes. These value-added processes are enhanced to value-added functions by input and output products. As an example the value-added function "primary forming" is illustrated above in Figure 5.

By integrating resource and order object classes the value-added function is enhanced to a value-added activity. Figure 6 shows resource and object classes for manufacturing. Resources encompass employees, equipment, supplies, IT-systems, capital expenditures and knowledge. All resources to execute manufacturing operations can be modeled. Employees are differentiated into sub-classes according to their qualification level. Equipment includes machines, tools and devices, which are used to carry out the manufacturing process (Gienke and Kämpf, 2007). Further manufacturing equipment are measuring instruments, logistics, buildings and supplies. The remaining resource object classes are consumables, IT-systems, capital expenditures and knowledge.

Order object classes activate the value-added function and are structured into the sub-classes strategy, company profile and sector profile. The strategy class differentiates itself in further object classes "corporate strategy" and "internationalization strategy." In the next step, characteristics are developed for each object class structure. Characteristics are essential as they are used to fill the benchmarking database with information. They describe each object class. So, each object class has been characterized. The characteristic categories can be distinguished into:

(1) functional characteristics (referring to process and products);

(2) resource object class characteristics; and

(3) order object class characteristics.

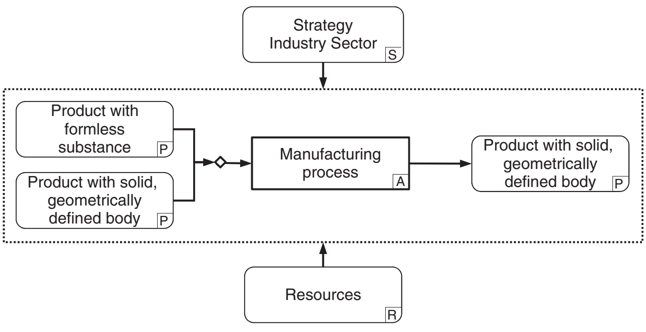


Figure 4.
Generic Activity Model of manufacturing processes

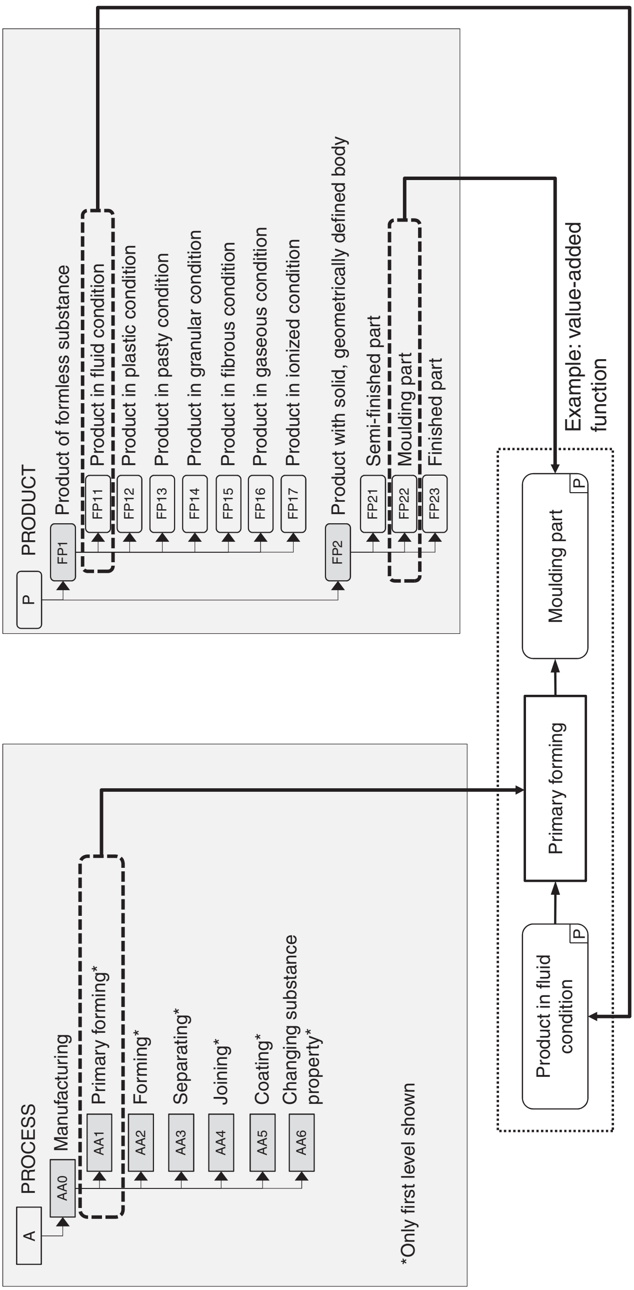


Figure 5.
Function object classes comprise process and product object classes

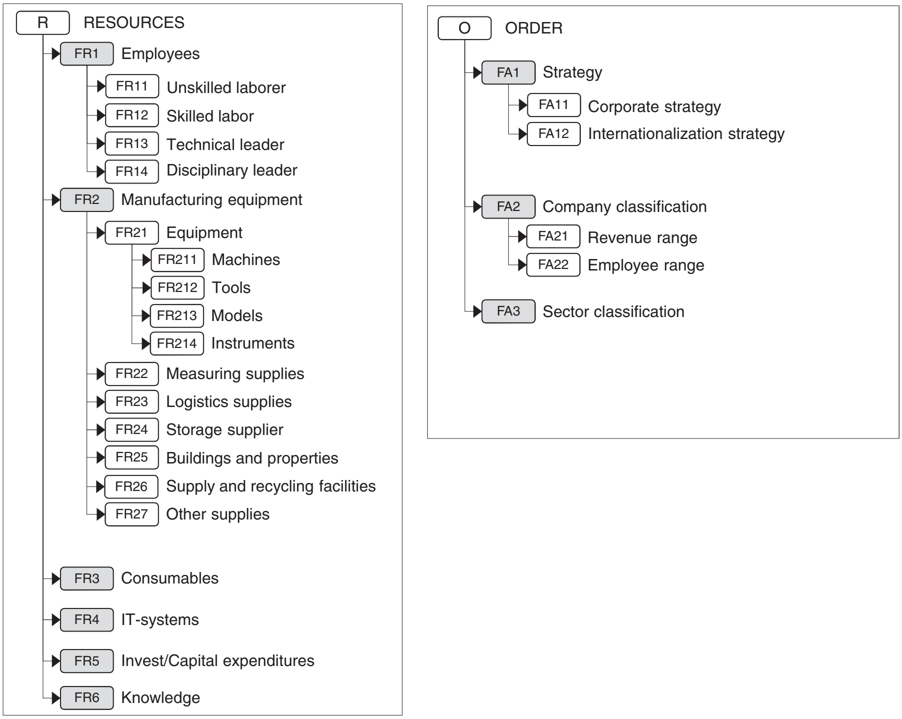


Figure 6.
Resource and order object classes (manufacturing)

Characteristics are defined by indicators. They are specifically designed for manufacturing processes for the benchmarking database. In total, they encompass more than 40 indicators. In this paper, the focus is on the key indicator groups grouped by function, resource and order object classes.

Functional characteristics describe the dedicated process in combination with input and output products. Process and product characteristics are merely descriptive without evaluating the function. Thus, value-added functions are objectively comparable on an abstracted level based on process and product characteristics. Moreover, the pure process can be benchmarked independently of product characteristics. The descriptive characteristics for output products enable process-independent product benchmarking, by applying benchmarking filters only to the initial product characteristics identifying best practice processes.

Characteristics describing resource object classes are primarily associated to a specific location. In contrast to the functional characteristics, resource characteristics are of evaluative character, by assessing the function in terms of performance, cost and quality. In addition, they have more characteristics describing the process. Overall, resource characteristics within "manufacturing" are structured in the categories location, organization, relocation, cost, performance and quality:

- Location characteristics describe the geographical production site on which the manufacturing function takes place.
- Organizational characteristics determine the organization of physical and human resources. Essential elements are the industrial production type (mass vs individual), the production organization, the degree of automation and the number of differently qualified employees needed for this process.

- Relocation characteristics are associated to potential footprint redesign and comprise of ramp-up performance and local procurement characteristics of resources. They are only applicable to those processes with footprint experiences.
- Cost characteristics are the financial evaluation criterion for the resources used. They include personnel, equipment and supplies related to the manufacturing process and are defined according to a set standard.
- Further categories of evaluating resources are performance and quality characteristics. Performance is measured in terms of employee-specific and technical-specific perspectives. Employee-specific performance criteria, for instance, include sickness absence rate, fluctuation, motivation and qualification level. Technical-specific performance criteria are measured by equipment availability, productivity and flexibility. Both performance and quality characteristics are measured by indicators referring to common industry standard.

Order characteristics are aligned to the order object classes strategy, company profile and sector profile. Strategy itself is differentiated between corporate and internationalization strategy. The corporate strategic characteristics are structured into product program, competition, activity and resource strategy (Bleicher, 2011). The internationalization strategic characteristics are cost reduction, following customer, technology and market access. The company profile is determined by revenue and number of employees. The sector profile is organized according to the German classification for industry (Figure 7).

As a result, the benchmarking database is structured in object class hierarchies that are characterized by those specified indicators. They are the foundation for modeling value-added processes. The literature review considers the opposing process modeling approach using ontologies and meta-models to describe network-based interrelationships rather than having hierarchies of object classes (Teuteberg *et al.*, 2013). This approach, however, is not suitable for these modeling purposes as Teuteberg *et al.* (2013) compare process models in terms of syntax and semantics.

3. Methodology: five steps of modeling value-added processes

The modeling tool includes five steps. In steps 1-4 the components of the Generic Activity Model are successively built up. The first step is setting the modeling scope. That means that one competitive business area has to be selected and its corresponding database that can be manufacturing, product development or assembly. (Figures 8 and 9).

The second step is the selection of sub-functions of the function class hierarchy and the process visualization of these sub-functions. This visual illustration of the value-added process sequence on function level embodies the modeling framework.

The third step enhances the existing functions by integrating input and output product object classes. For this purpose, input and output products from full-scale product object class hierarchy benchmarking database are assigned to each process. As a result, the sequence of value-added processes can be enhanced to value-added functions (Figure 10).

In the fourth step, value-added functions are enhanced to value-added activities. This takes place by assigning resource object and order object classes to each value-added function. The resource and order object classes are selected from the resource object class and order object classes hierarchies, respectively (Figure 11).

In the fifth step, all object classes are characterized for each value-added activity. This includes functional characteristics, resource object class characteristics and order object class characteristics. As stated above, each business area (manufacturing, assembly and product development) has its specific characteristics structure that can describe any business area-specific object classes (Figure 12).

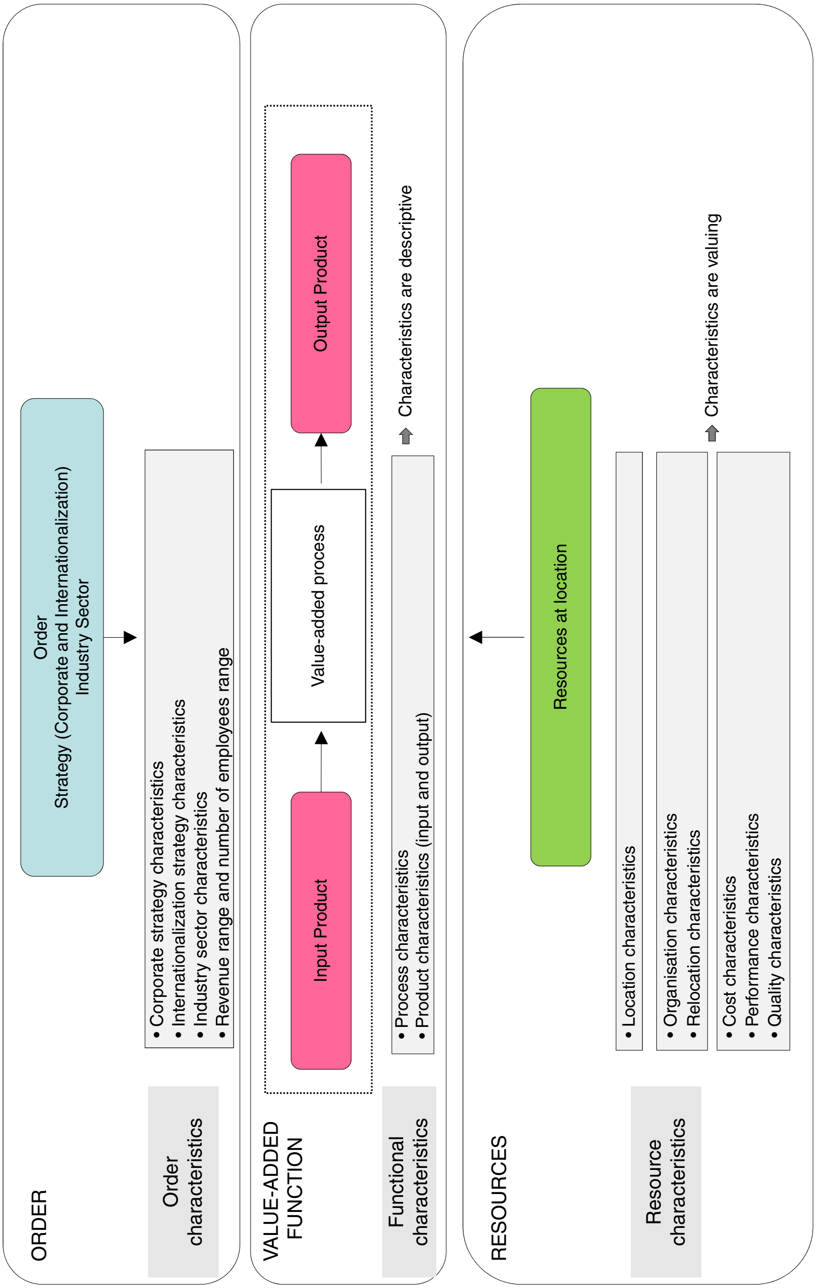


Figure 7.
Object and function classes are characterized – overview on order, functional and resource characteristics

In general, the modeling tool has normalized value-added processes using standardized object and function classes. The final integration of measurable indicators through the characterization in the fifth modeling stage provides the database for the benchmarking evaluations.

4. Benchmarking

The main instrument for benchmarking is the individual combination of characteristics using a so-called filter matrix. Given the top management evaluation task, the filter matrix is used to select the combination of relevant benchmarking characteristics. On the basis of typical strategic questions some common benchmarking filter combinations can be formulated. The chosen benchmarking filter combinations result in respective benchmarking profiles. Each benchmarking profile has its own benchmarking performance level. The benchmarking performance level is defined by its degree of independence in terms of location, product, processes and industry sector. The fact of identifying and transferring best practices across processes, sectors and locations is associated with the higher level of benchmarking performance. For instance, similar best practices are superior if they are generic processes rather than being found among direct product competitors (Camp, 1989). A prominent example is the aforementioned product-independent benchmarking between the chocolate manufacturer and the circuit board manufacturer in the electronics industry. The best practice in mounting process was found with the chocolate manufacturer (Mertins and Kohl, 2009). All benchmarking profiles can be classified to the benchmarking performance level and be located within a portfolio matrix.

Typical top management questions are translated into a benchmarking filter combination based on the characteristic structure. This characterization of the evaluation question is achieved through parameterization using those characteristics. A filter logic is used by the creation of characteristic combination pairs. The matrix (see Figure 13) lists the options available for characteristics combinations. Order, resource and functional characteristics are displayed alongside both vertical and horizontal axis.

A question is characterized by fixing at least two characteristics as a benchmarking filter, while the characteristics to be evaluated correspond to the primary or secondary evaluation attributes. In principle, fixed filter parameters impose requirements on potential management question.

The more characteristics are fixed, the more precisely a question can be characterized. Fixed characteristics are denominated by capital letters (S, B, X, R, A, P) whereas variable characteristics to be valued are denominated by small letters (*s*, *b*, *x*, *r*, *a*, *p*). If both process (A) and product (P) are fixed, they always form the value-added function (functional unit of product and process). Process (A) itself would represent the value-added process itself.

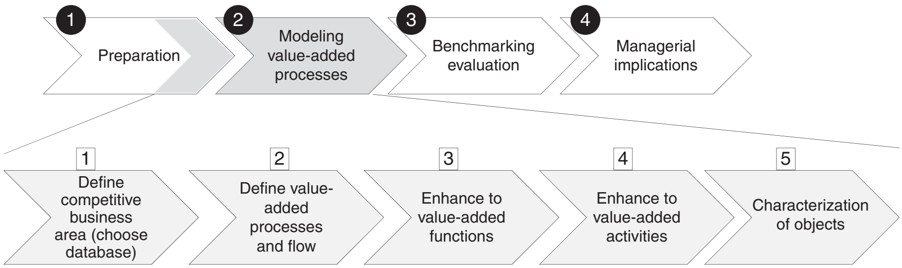


Figure 8.
Five steps approach of modeling value-added processes

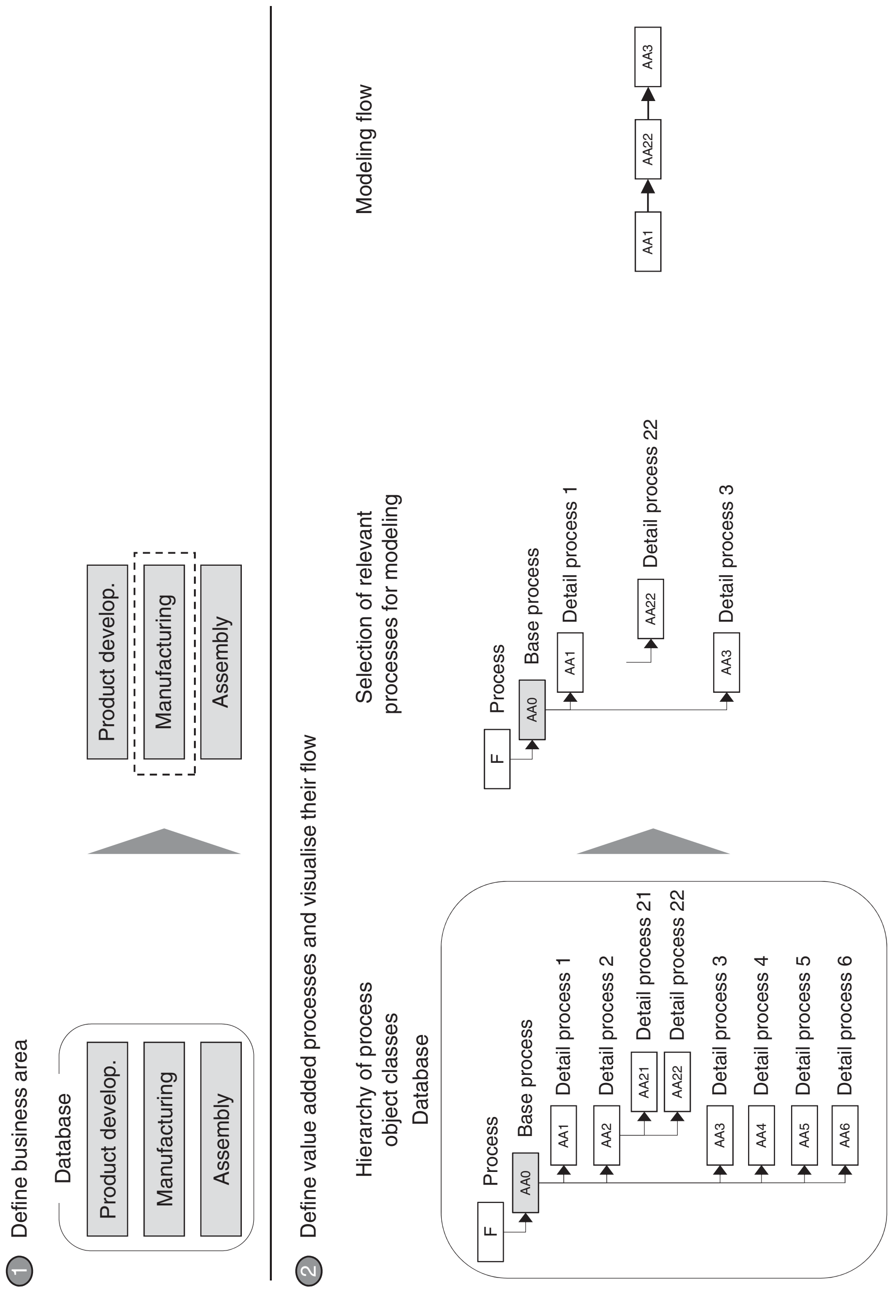


Figure 9.
First and second modeling steps of value-added processes

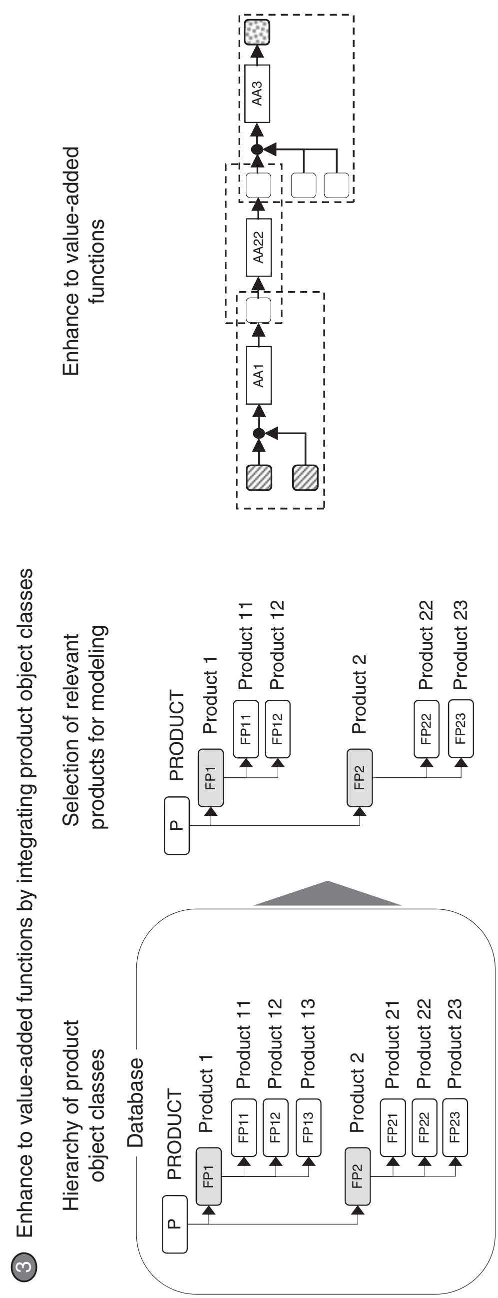


Figure 10.
Third modeling step of value-added processes

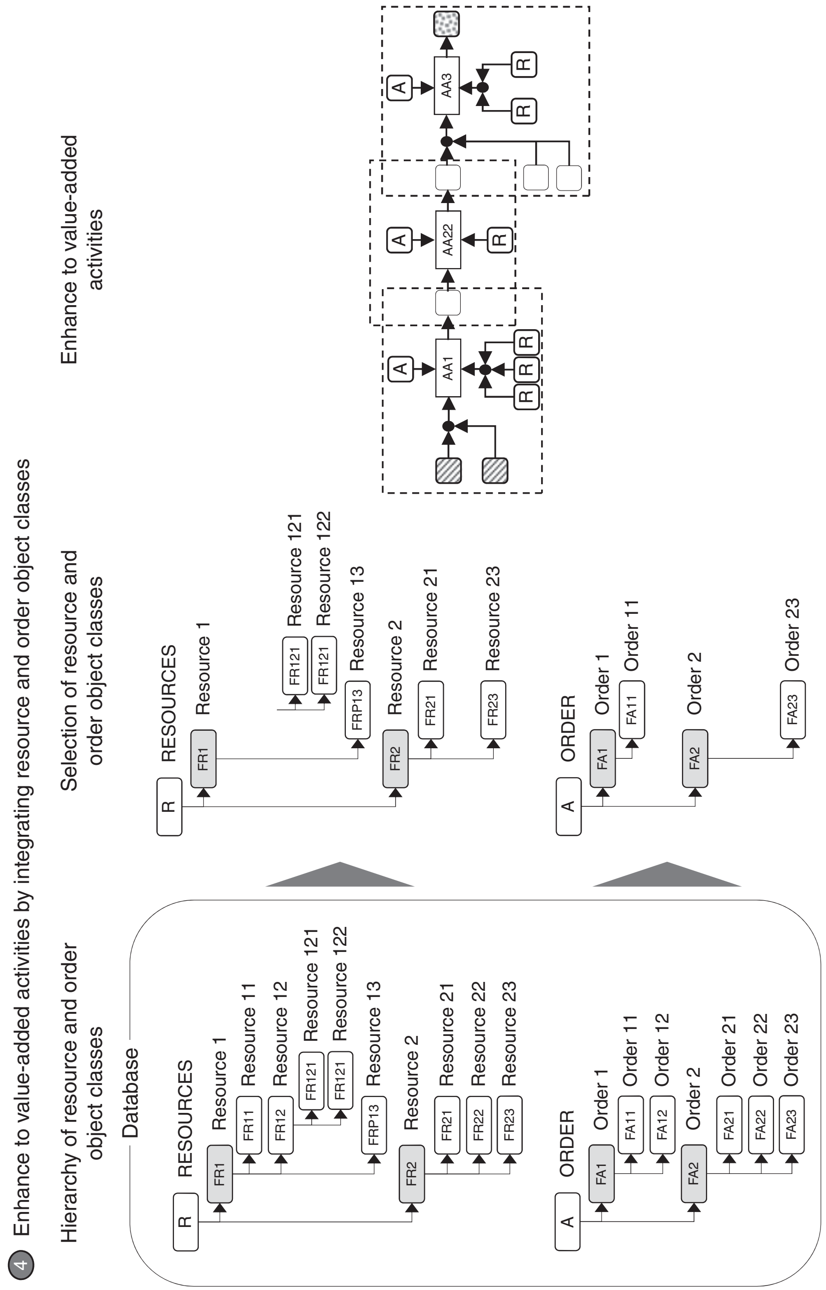


Figure 11.
Fourth modeling step

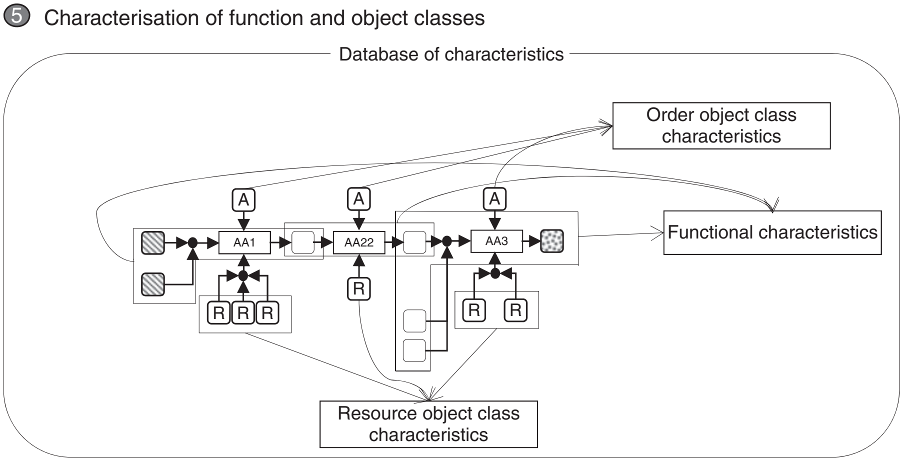


Figure 12.
Fifth modeling step

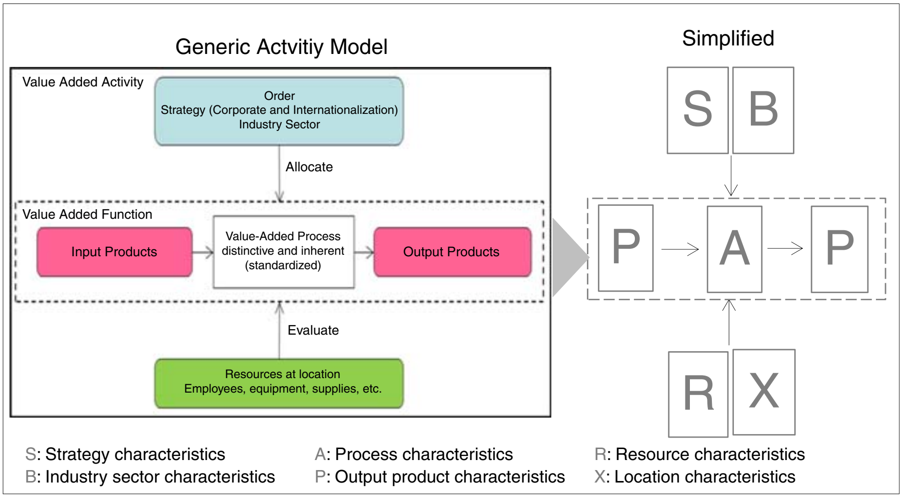
Some typical questions can be emerged from the large number of theoretically possible filter combinations. The question usually refers to the primary evaluation attribute. Depending on the evaluation requirement a secondary evaluation attribute can be useful, that is built on the primary evaluation attribute.

As depicted in Table I, key evaluation questions representing typical top entrepreneurial decisions have developed and categorized. Questions 1-3 represent typical production footprint evaluations. Questions 4-8 relate to the performance evaluation of resource characteristics that perform the value-added processes. On the other hand, questions 9 to 15 search for the optimal production site given requirements stated by resource, industry, strategy or functional characteristics. In particular, question 15 defines location requirements for a specific value-added process from a resource-based view. Thus, question 15 simply represents typical location criteria in the context of site locations or footprint analysis (Table II).

Our portfolio matrix in Figure 14 classifies pre-selected combinations into different benchmarking performance levels. The performance level is determined by the degree of independence regarding product, process, sector and location. These four performance dimensions are sufficient to address various benchmarking evaluation tasks. The portfolio matrix shows that the sector-, location- and product-independent benchmarking type offers the highest benchmarking performance level. This perfectly corresponds to the higher level of benchmarking ambition outlined by Töpfer (1997). The higher the degree of independence the higher the benchmarking performance level will be.

It should be noted that in the case of concurrent product and process independence (quadrant I1) there is always a functional independence since variable characteristics process (*a*) and product (*p*) form a functional unit. Contrary, a dependence is implied on the value-added function (AP) in quadrant III1, if concurrent product and process independence exists

In the illustration above includes some representative combination cases. According to Camp (1989), the filter combinations no. 5, 21 or 26 belong to the group "direct product competitors" and nos 28 and 33 refer to the group "generic processes." Furthermore, the combination of no. 21 represents the aforesaid product-independent benchmarking example between the chocolate manufacturer and the circuit board manufacturer in the electronics industry in terms of mapping the best practice in mounting process (Mertins and Kohl, 2009). On the basis of similar process characteristics (A) (e.g. cleanroom condition) and similar product characteristics (P) (e.g. small, isolated parts in mass number) case no. 21



			Order object class		Resource object class		Function class	
			S	B	X	R	A	P
			Strategy	Sector	Location	Resource	Process	Output Product
Order object class	S	Strategy		a Process p Output Prod. r Resource x Location	a Process p Output Prod. r Resource b Sector	a Process p Output Prod. x Location b Sector	b Sector x Location r Resource p Output Prod.	b Sector x Location r Resource a Process
	B	Sector			a Process p Output Prod. s Strategy r Resource	a Process p Output Prod. s Strategy x Location	s Strategy x Location r Resource p Output Prod.	s Strategy x Location r Resource a Process
Resource object class	X	Location				a Process p Output Prod. s Strategy b Sector	s Strategy b Sector r Resource p Output Prod.	s Strategy b Sector r Resource a Process
	R	Resource					x Location b Sector s Strategy p Output Prod.	x Location b Sector s Strategy a Process
Function class	A	Process						x Location b Sector s Strategy r Resource
	P	Output Product						

Figure 13.
Benchmarking filter matrix with fixed (axis, capital letters) and variable (middle, small letters) characteristics

would reveal the benchmarking industry sector (*b*) (chocolate) with its superior mounting process capabilities.

Furthermore, case no. 22 or 23 can further seek for the root cause for the superior mounting process by evaluating the process characteristics *(r)* or the site characteristics *(x)*. They refer to process benchmarking (Siebert, 1998).

Cases no. 21-23 comprise characteristics combinations which depend on value-added functions as process and product characteristics are fixed.

	Fixed characteristics		Primary evaluation attribute	Secondary evaluation attribute	Benchmarking evaluation questions (examples)
					Focus: location-independent evaluation of value-added function characteristics
1	X	B, S	*ap*		Which value-added function (*ap*) with specific process (A) and product (P) characteristics are executed at location (X) in the industry sector (B) following the strategy setting (S)?
2	X	B	*ap*		Which value-added function (*ap*) with specific process (A) and product (P) characteristics are executed at location (X) in the industry sector (B)?
3	X	S	*ap*		Which value-added function (*ap*) with specific process (A) and product (P) characteristics are executed at location (X) following the strategy setting (S)?
					Focus: location-dependent evaluation of resource characteristics
4	X	B, S, A, P	*r*		How are resource characteristics (*r*) evaluated of the value-added function (AP) at location (X) in sector (B) following strategy (S)?
5	X	A, P	*r*		How are resource characteristics (*r*) evaluated of the value-added function (AP) at location (X)?
6	X	A, P, B	*r*		How are resource characteristics (*r*) evaluated of the value-added function (AP) at location (X) in sector (B)?
7	X	A, P, S	*r*		How are resource characteristics (*r*) evaluated of the value-added function (AP) at location (X) following strategy (S)?
8	X	A	*r*		How are resource characteristics (*r*) evaluated of the value-added process (A) at location (X)?
					Focus: footprint analysis/site location analysis
9	S	A	*x*		Which locations (*x*) are chosen by companies with value-added process (A) following strategy (S)?
10	B	A, P	*x*		Which locations (*x*) are chosen by companies in sector (B) with the value-added functions (AP)?
11	B	A, P, S	*x*		Which locations (*x*) are chosen by companies in sector (B) with the value-added functions (AP) following strategy (S)?
12	S	B	*x*		Which locations (*x*) are chosen by companies in sector (B) following strategy (S)?
13	P		*x*		Which locations (*x*) are chosen by companies with the value-added process (A)?
14	S		*x*		Which locations (*x*) are chosen by companies following strategy (S)?
15	R	A	*x*		Which locations (*x*) are chosen by companies with the value-added process (A) operated by resources (R)?
					Focus: location-dependent analysis of output product characteristics
16	X	B	*p*		Which output product characteristics (*p*) are produced at location (X) by companies from sector (B)?
17	X	B, S	*p*		Which output product characteristics (*p*) are produced at location (X) by companies from sector (B) following strategy (S)?
18	X	S	*p*		Which output product characteristics (*p*) are produced at location (X) by companies following strategy (S)?
					Fokus: location-dependent analysis of strategy characteristics
19	X	B	*s*		Which strategy (*s*) is followed by companies at location (X) in sector (B)?
20	X	P	*s*		Which strategy (*s*) is followed by companies at location (X) producing products (P)?

Table I.
Sample benchmarking evaluation questions are characterized by the filter matrix

	Fixed characteristics		Primary evaluation attribute	Secondary evaluation attribute	Benchmarking evaluation questions (examples)
					Location and sector independent best practice processes
21	A	P	*b*		In which sectors do we have similar value-added functions that have the similar process (A) and product (P) characteristics?
22	A	P	*r*	*b*	Primary: analysis of resource characteristics (*r*) for the value-added function (AP) Secondary: in which sectors are the best evaluations (*r*) for those value-added function (AP)?
23	A	P	*r*	*x*	Primary: analysis of resource characteristics (*r*) for the value-added function (AP) Secondary: where (locations x) are the best evaluations for those value-added function (AP)?
24	B	P	*r*		Sector champion: who has the best evaluation in terms of resource characteristics (R) regarding product (P) in sector (B)?
					Process-independent evaluation (e.g. alternatives of manufacturing technologies and location-specification of manufacturing technology)
25	P		*a*		Manufacturing technology alternatives: which manufacturing technologies (*a*) are applied to produce product (P)?
26	P	X	*a*		Location-specification of manufacturing technology: which manufacturing technologies (*a*) are applied to produce product (P) at location (X)?
27	P	B	*a*		Manufacturing technology alternatives: which manufacturing technologies (*a*) are applied to produce product (P) in sector (B)?
					Product-independent evaluation (global benchmarking view)
28	A		*p*	*b*	Primary: which products (*p*) are produced by the identical or similar manufacturing technology (A)? Secondary: in which sectors (*b*) are they?
29	A	R	*p*	*b*	Primary: which products (*p*) are produced by the identical or similar manufacturing technology (A) with the same resource characteristics (R)? Secondary: in which sectors (*b*) are they?
30	A		*b*	*x*	Primary: in which sectors (*b*) is process (A) applied? Secondary: where (location x) are they?
31	A	R	*b*	*x*	Primary: in which sectors (*b*) is process (A) applied and operated by resources (R)? Secondary: where (location *x*) are they?
32	A		*r*	*x*	Primary: analysis of resource characteristics (*r*) used for process (A) Secondary: where (location *x*) are they?
33	A		*r*	*b*	Primary: analysis of resource characteristics (*r*) used for process (A) Secondary: in which sectors (*b*) do we find these resources (*r*) with the best evaluations?

Table II. Sample benchmarking evaluations with secondary evaluation attributes

Cases no. 25-27 refer to the process-independent evaluation aiming at identifying technological manufacturing alternatives. This is essential in order to adapt manufacturing technologies to the site location.

Cases no. 28-33 discuss product and sector independent benchmarking and requires a precise characterization of the value-added process (A) to enable a global comparison.

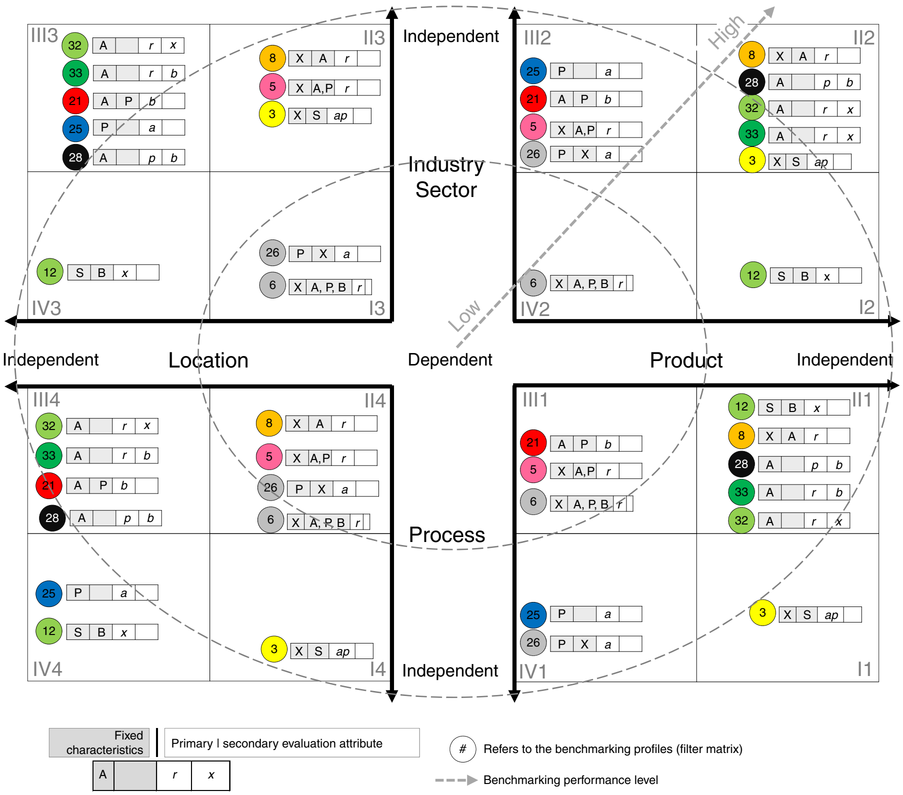


Figure 14.
Portfolio matrix to depict characteristics combinations and benchmarking performance level

Product-independent process benchmarking may also be applied to supportability which is referred to the company's capability to provide support services (Asjad *et al.*, 2012, 2014). Independent of the physical product, related services such as maintenance and logistics can be analyzed and transferred. Margins derived from services contracts are usually higher than from the physical product throughout its life cycle. In the last years, German mid-sized companies have successfully extended their service ranges to justify their price premium and thus, enhanced customer loyalty. Asjad has developed conceptual frameworks (Asjad *et al.*, 2012) for supportability analyses as well as methods and empirical studies to arrive to optimal contract structure based on minimum life cycle cost (Asjad *et al.*, 2015).

It is advised for corporate strategy departments to apply cases 30-33 on a regular base to identify industry best practices.

Both extreme profiles high and low level of benchmarking performance can be shown in the portfolio matrix. In most cases, it is useful to think beyond the original top management evaluation task by choosing further filter combinations that can lead you to a higher benchmarking performance level. This supports continuous improvement of the organization and challenges existing solutions or frameworks (Figure 15).

5. Case study: site location analysis through product-independent process benchmarking

Structural parts made of carbon fiber composite materials are used in the automotive industries and are characterized by their solidity and light weight. It has been a mature

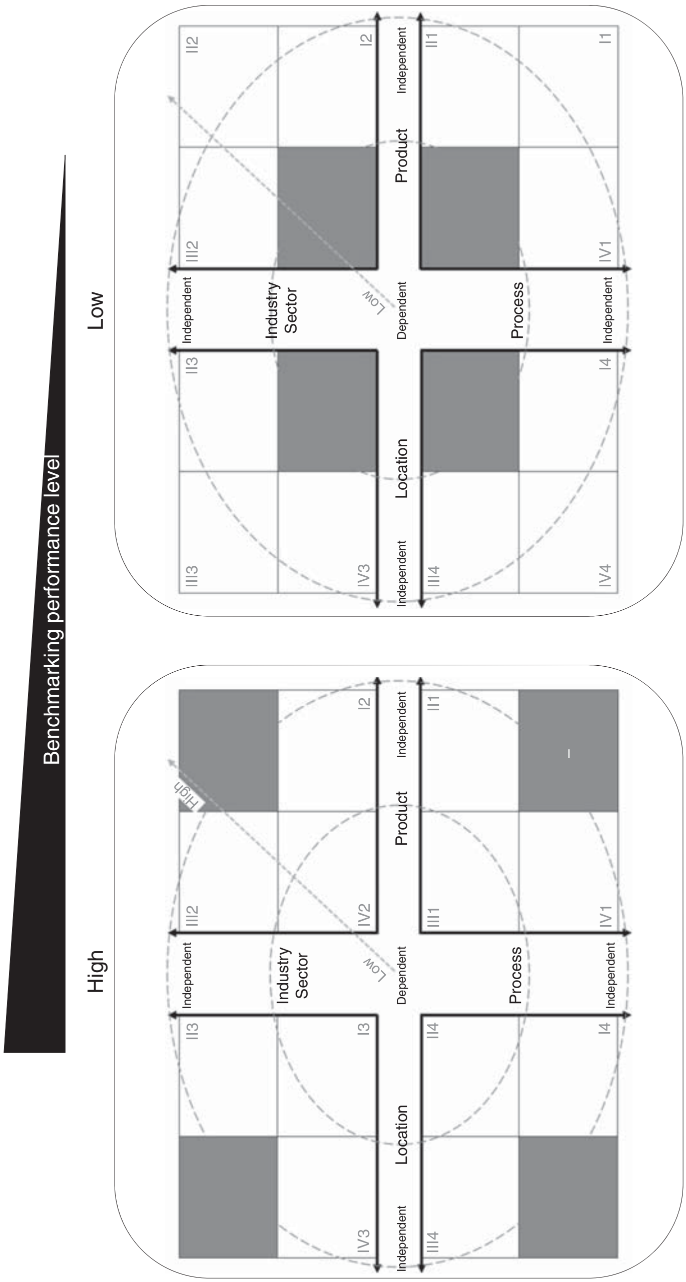


Figure 15.
High and lower benchmarking performance levels

technology for decades; however, the industrialization and automation of its production process are still technological challenges. The mass production does not seem to be an easy journey for high complex parts. The core competencies lie in the production of raw materials and the manufacturing process, which is characterized by a high degree of manual labor for complex parts. Complexity is often characterized by the number of different layers required and the curving dimensions. The higher degree of manual work compared to other manufacturing industries is due to individual, cut layer of carbon fiber and reinforcing glass fiber which both have to be manually laminated according to the shape requirement of the part. Each part has its own individually designed tool. The more complex and larger the part (e.g. sills, fender and hood), the more extensive is the lamination process. For instance, a side sill in the automotive application field may consist of up to more than 200 individual layers. The lamination process itself is subject to time-critical parameters, because of the resin being liquid at room temperature and easily sticks. The laminated part is then hardened under vacuum condition and heated. After a defined process time the part is being removed manually from the mould. The next steps are machining such as CNC and painting. Therefore, mastering the lamination process is a key success factor. The question is where to invest a factory to produce at optimal conditions. High-performance benchmarking can support the site planning and can significantly contribute to the decision-making process.

The study is carried out in three phases:

- Phase 1: understand company and its strategy.
- Phase 2: modeling value-added processes.
- Phase 3: benchmarking and deriving managerial implications.

In the first phase, the company and its strategy have been analyzed. It is headquartered including its development department in Western Europe. The company has extensive know-how in the production of raw materials carbon and fiberglass. As a new strategic business segment, the applications of carbon fiber composites will be expanded to the automotive industry. Furthermore, the product program strategy is following a niche program. The competitive strategy is based on innovation and first-mover advantages. The full integration of the value chain from raw material production, lamination to mechanical processing is of strategic importance.

The internationalization strategy states that the new production facility should include the complete value chain from raw material production, lamination and machining steps. The location should be logistically well connected to the end-customer and ideally to paint shops. Body parts are not classical just-in-time parts for automotive OEM customers and thus can be delivered in batches. A close distance to OEM factories is not required, but desirable. An important success factor is the implementation of the lamination process for small series of exclusive car manufacturers, which is the target customer group.

For the foreseeable future body parts with direct customer visibility made from carbon fiber composites will play a significant role in the higher-priced car segment. Thus, these parts are of high complexity due to their shapes and visibility to customer. The lamination competence of labor is a key success factor for production and consequently will be considered as the primary evaluation characteristic in the benchmarking phase.

Modeling the manufacturing value chain

The modeling focus is on the lamination process. All object and functional classes with their characteristics structure serve as the benchmarking database for the modeling exercise.

The modeling follows the five steps approach. In the first step, the flow of value-added processes has been modeled.

The normalized process "lamination" is standardized as "joining by press connection" which is a sub-group of "joining by mechanical means" that in turn refers to the family group of "joining" according to the German Institute for Standardization (DIN8593-3, 2003-09 (2003)) (Figure 16).

Value-added processes such as "knife cutting" are not critical regarding the site location and can be ignored in the investigation. In the next stage, value-added processes are enhanced to value-added functions by integrating input and output product classes (Figure 17).

The value-added function "joining by press connection" consists of layers as input products and the finished laminated part. The normalized product classes are named mouldings. The target shape is integrated in the tool. For complex parts the laminating and forming times take approximately two to four hours. By integrating resource and order object classes the value-added functions have been expanded to value-added activities.

In the final step, the functional class as well as resource and order object classes have been characterized. The focus is on the key characteristics which are relevant for the case study. Often the evaluation task defines what the relevant scope of characteristics is to be considered. Characterization of process and product object classes is essential as they will primarily serve as benchmarking filters. Key process characteristics are the normalized process name "joining by press connections," the manufacturing type (e.g. "piece production") and the number of manufacturing steps (150 steps).

The characteristics for input and output products will have detailed information on their material group. Thus, input products will have the names "glass fibre," "carbon fibre" and output products are being assigned the material group of "composites." Further output product characteristics are the number of annually produced parts as well as surface quality, indicated by the tolerance class "fine" (Tables III-V).

Characterizing resource object classes can be reduced to one crucial characteristic, the low degree of automation. This reflects the intensive manual effort for the lamination process. The full table of resource characteristics including the order characteristics is not shown.

Benchmarking evaluation and managerial implications

The evaluation objective is to identify optimal manufacturing locations for the lamination process. This determines the combination of the benchmarking filter matrix. The key question is geared to where similar or identical lamination processes can be found. Four iterative benchmarking filter combinations can be designed. The first question, for instance, has the process characteristics (A) and product (P) as well as resource (R) characteristics fixed as benchmarking filters. Fixed filter parameters impose the requirements to the potential site. The primary evaluation attribute is the industry sector (*b*) and the secondary evaluation attribute is the site location (*x*). The translation into the benchmarking evaluation question is found in Table VI. The same logic holds for the other three questions. In general, the low degree of automation as a resource characteristic is being fixed as a benchmarking filter for all questions.

While in evaluation questions 1 and 2 the input product (P) depends of the lamination process (normalized as "joining by press connection"), questions 3 and 4 refer to a product-independent process benchmarking. Question 4 enables a more global comparison based on the distinctive value-added process (A). Thus, questions 3 and 4 have a higher benchmarking performance level compared to 1 and 2 that mainly compare direct competitors. The benchmarking evaluation independent of the product, but with fixed process (A) and resource characteristics (R) reveal a new industry sector (*b*) with obviously a different product (*p*) that is "boat building" (findings derived from question 3). At the first glance, this is totally different to structural body parts in the automotive industry.

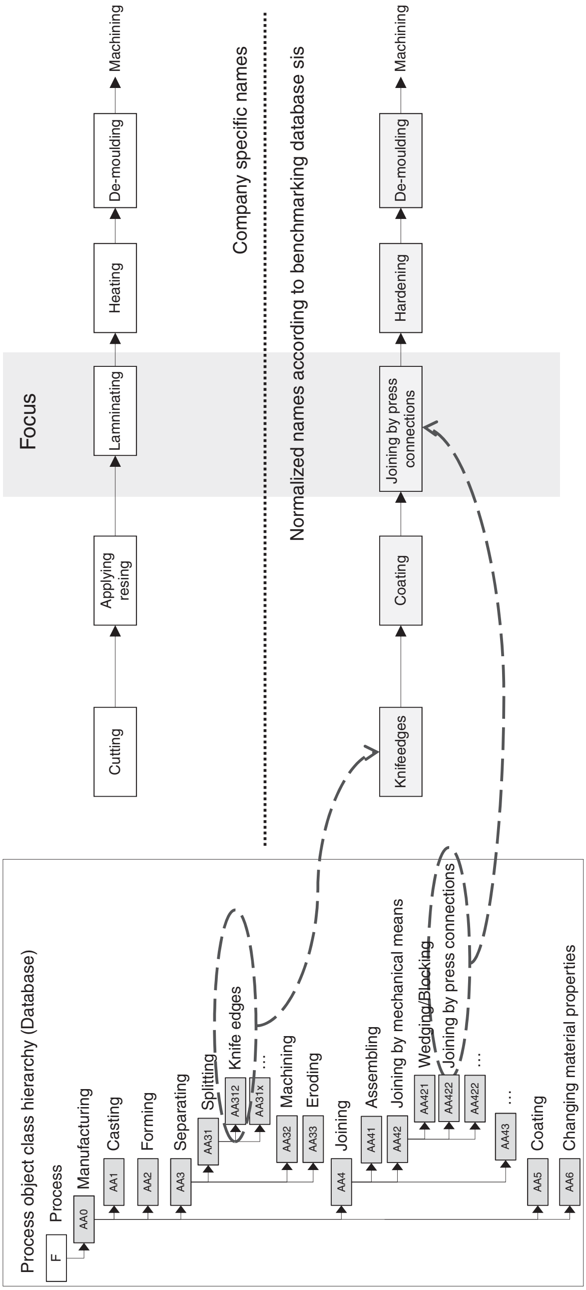


Figure 16.
Modeling the flow of value-added processes

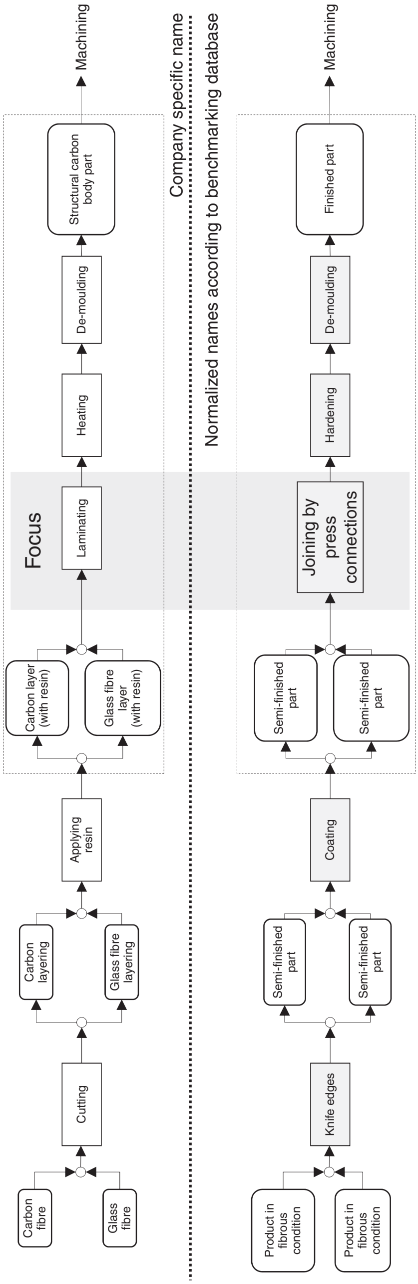


Figure 17.
Modeling value-added functions by integrating product object classes

Table III. Functional characteristics focused on process

Functional characteristics Characteristic	(Value-added activity = lamination) Value	 Definition
Specific name of manufacturing process	Lamination	Free text field
Function class 0	Manufacturing	Selection from database
Function class 1	Joining	Selection from database
Function class 2	Pressing	
Function class 3	Joining by press condition	Selection from database
Characteristics for the for industrial production type		
One-off production	–	(0: false; 1: true)
Small series production	ja	(0: false; 1: true)
Variant production	–	(0: false; 1: true)
Series production	nein	(0: false; 1: true)
Mass production	–	(0: false; 1: true)
Dimension characteristics		
Number of working steps within process	150	Number of working steps

Table IV. Functional characteristics focused on input products

Characteristic input products Characteristic	 Ausprägung	(Value-added activity = lamination)
Location	Germany	Selection from database
Specific name of input products	Glass fiber, carbon fiber	Free text field
Main characteristics		
Formless	No	(0: false; 1: true)
Solid and geometrically defined body	Yes	(0: false; 1: true)
Physiological characteristics		
Toxicity	No	(0: false; 1: true)
Requirements for sterile treatment	No	(0: false; 1: true)
Location characteristics		
Availability at location	Yes	(0: false; 1: true)
Complaint rate	1%	Number of rejected deliveries/total shipments
Supplier loyalty	100%	Number of parts scheduled delivered by the supplier/ total number of pledged for the period
Supplier performance	100%	Average actual quantity/promised average amount
Number of suppliers	13	Number of local, substitutable suppliers
More intensive supplier development necessary	Yes	(0: false; 1: true)
Possibility of purchasing pools	No	(0: false; 1: true)

The competence of manual lamination in boat construction is traditionally strong, because different reinforcing and sealing fibers are laminated on the lower bottom of a boat.

Based on the sector (*b*) findings from the primary evaluation attribute the location characteristic (*x*) as the secondary evaluation attribute has been further applied. The finding reveals that this industry is increasingly to be found in coastal areas. Obviously, competence clusters of expertise in laminating boats are formed in certain coastal regions.

This result shows that regardless of the final product the same characteristics of the distinctive value chain "joining by press connections" can lead to valuable benchmarking

Characteristic output products	(Value-added activity = lamination)	
Characteristic	Ausprägung	
Location	–	Selection from database
Specific name of input products	Structural carbon body part	Free text field
Characteristics of product geometry		
Number of edges	6	Value range
Number of round surfaces	3	Value range
Nominal outer diameter	1,100 mm	Value range
Length dimension by which the product is defined	1,200 mm	Value range
Tolerance class	Fine	(Fine, middle, rough, very rough) industry standard definition
Characteristics of material group		
Metal		
Ferrous metal	No	(0: false; 1: true)
Non-ferrous metal	Yes	(0: false; 1: true)
Non-metal		
Semiconductor	No	(0: false; 1: true)
Non-metallic - inorganic material	No	(0: false; 1: true)
Polymers	Yes	(0: false; 1: true)
Natural Products	No	(0: false; 1: true)
Mineral natural products	No	(0: false; 1: true)
Organic natural product	No	(0: false; 1: true)
Composite material	Yes	(0: false; 1: true)
Economic characteristics		
Volume/Number of pieces p.a.	1,000	Value range
Number of variants	2	Value range
Average daily stock of finished goods	–	Value range
Physiological characteristics		
Requirements for sterile treatment	Yes	(0: false; 1: true)
Toxicity	No	(0: false; 1: true)
Location characteristics		
Site-specific product geometry adjustment	No	(0: false; 1: true)
Site-specific substance property adjustment	No	(0: false; 1: true)
Site-specific packaging adaptation	No	(0: false; 1: true)

Table V. Functional characteristics focused on output products

partners. In this case study this company has invested in a coastal location where boat building has a long tradition. There are many skilled workers who are familiar with the composite material as working material. The site location identified is situated on an island with high availability of qualified laminators and their short training periods turned out to be an essential success factor. The lot size production also justifies longer distances to the OEM factory. Over the years, also other composite factories from other industry sectors have settled on this island.

Transferring this case into the portfolio matrix one can examine the benchmarking profiles in terms of their benchmarking performance level. Benchmarking profiles are determined by the evaluation questions and filter combinations applied. The independence of location and industry sectors foster the global benchmarking character in this case study. Due to the focus on the lamination process consistent process dependence has been

	Fixed characteristics		Primary evaluation attribute	Secondary evaluation attribute	Benchmarking evaluation questions
					Focus: site location search
1	A	P, R	*b*	*x*	Primary: in which sector (*b*) we can find similar or identical value-added functions (AP) (process: "Joining by press connections" and product: "composite material") as well as with the resource characteristic (R) of "low automation degree?" Secondary: at which locations (*x*) these companies from sector (*b*) can be found?
2	A	P	*b*	*x*	Primary: in which sector (*b*) we can find similar or identical value-added functions (AP) (process: "Joining by press connections" and product: "composite material")? Secondary: at which locations (*x*) these companies from sector (*b*) can be found?
3	A	R	*b*	*x*	Primary: in which sector (*b*) we can find similar or identical value-added processes (A) (process: "Joining by press connections") with the resource characteristic (R) of "low automation degree"? Secondary: at which locations (*x*) these companies from sector (*b*) can be found?
4	A		*p*	*b*	Primary: which products (*p*) are produced through the similar or identical value-added process (A) (process: "Joining by press connections?") Secondary: In which sectors (*b*) these products (*p*) can be found?

Table VI. Selected benchmarking evaluation questions and their characterization

necessary. Both product-independent and product-dependent cases have been analyzed. The product-independent investigation revealed more options and thus brought up a higher level of benchmarking performance (Figure 18).

6. Conclusion

Benchmarking is a common management tool that gives orientation and is used for evaluations of the companies' processes. This research contributes to the set of instruments for benchmarking processes. The modular analysis kit of different benchmarking databases for the business areas such as manufacturing, assembly and product development controls complexity and ensures scalability. Modeling value-added processes can be used as a simulation tool for projects in early planning stages. Particularly, this tool can be used for location and factory footprint analysis. The prospect of assessing manufacturing technology requirements that are driven by location factors is of important practical relevance (Khanna, 2014; Meyer, 2006).

The modular design of object and function classes is favorable. Depending on entrepreneurial questions, the depth of analysis is scalable. Different depths along the hierarchies can be selected to model value-added processes, functions and activities. The characteristic structure of the database is not a mere collection of information and data points, but it has been designed to relevant practical issues. In practice, it can be shown that the filling of the required database fields is manageable in less than an hour for a process with four to six working steps.

The trend toward the effective processing of large amounts of data will support the growth of this database. New insights are derived from large data sets and their combinations. A web-based collaboration platform would accelerate the database growth. Hence, the benchmarking methodology should generally be tested in the light of new

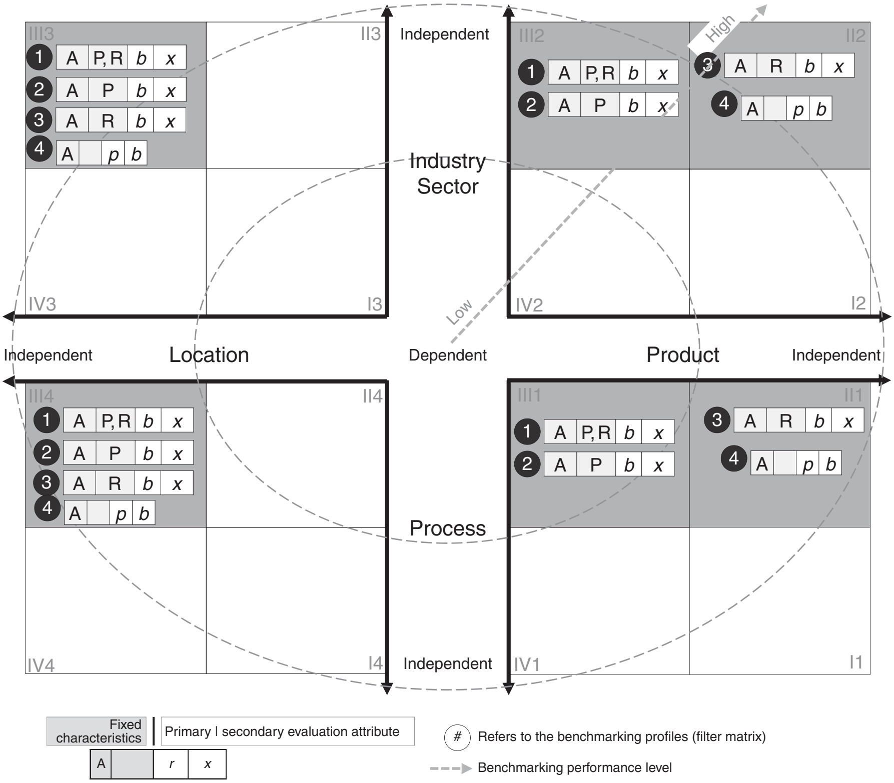


Figure 18.
Portfolio matrix showing benchmarking profiles applied in case study

technological, internet-based developments. Data collection and data analysis represent development opportunities for benchmarking engineering.

In pursuing high-performance benchmarking, yet one should be aware of the basic rule that benchmarking solutions are only as good as the benchmarking partners (Mertins *et al.*, 1995). The ability to achieve higher levels of performance in benchmarking in the sense of an increasing degree of autonomy in terms of location, industry, process and product should be used for business decisions. This can also take place in form of regular strategy reviews. Moreover, the approach of the portfolio matrix helps to make this global benchmarking measurable. The framework portfolio matrix serves as a navigation map to reassess benchmarking profiles in terms of their performance level. Principally, the portfolio matrix should show the user how to navigate his individual benchmarking task and even to reach a higher performance benchmarking level.

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Corresponding author
Xing Zhou can be contacted at: xing.zhou@campus.tu-berlin.de