3. Customized product configuration with a QFD-based knowledge base

3.1. Knowledge representation

Product adaptation needs knowledge in the field of product and production process redesign. Product adaptations consist in changing technical documentation of products from the enterprise product portfolio. To support the redesign of product configuration, it is necessary to know the answers to the following questions [31]:

- What are the main product features noticed by the customer?
- What are the main product features noticed by the producer? Is it necessary to select the most important product engineering and trade characteristics and specify target product characteristics?
- What is the product structure?
- What kinds of changes are necessary to introduce to the product?
- What product or product part from the product portfolio is close to customer requirements?
- Which product parts have to be redesigned?
- What is the risk regarding product failure?
- What product engineering and trade characteristics can be offered to the client?

QFD-based knowledge base (QFD-KB) for product configuration needs proper methods of knowledge representation. There is plenty of research work focused on gap analysis between knowledge area, knowledge type, and methods of data analysis [32, 33].

Knowledge comes from different sources and could have a different form. Knowledge could be tacit, which means preverbal—understood as unvoiced—unspoken, intuitive and emotional. On the other hand, explicit knowledge is expressed clearly, verbally or in mathematical models [34].

Knowledge should be codified and stored in a way that enables other people to understand and reuse it easily [34].

Formal description of knowledge is called knowledge representation. According to the level of formalism used for knowledge representation, we can distinguish procedural knowledge, which defines algorithms that help to achieve given goals, and declarative knowledge, which gives the solution without analyzing the problem structure.

There are different methods and tools which could be used for knowledge representation. Knowledge representation methods include, among others [34]:

- Decision rules—which contain expressions such as IF $x1$ is $F1$ **and/or** $x2$ is $F2$ **and/or** … xn is Fn, THEN y is P where $x1, x2, \ldots.. xn, y$ denotes objects or attributes and $F1, F2, \ldots\ldots Fn, P$ denote values. Decision rules describe both information elements (expressions) and relations between them, and therefore, a set of such rules (r) defines a knowledge base: $KB = \{r1, r2,\ldots\}$.
- Decision trees—which are graph representations of the decision process. The inspection of the condition in the decision path starts from the beginning node called the root and ends in the leaves which give the decision.
- Frames are used when information units are characterized by many important features. The structure of a simple frame contains three different lines: a heading with the frame name, a pointer to another frame with appropriate relation, and slots defining attribute names and values.
- Semantic networks capture knowledge as a graph, in which nodes represent pieces of information (objects, concepts, or situations in the problem domain), and the arcs represent relations or associations between them.
- Artificial neural networks (ANNs) are inspired by neurons in the brain and have become a popular knowledge representation useful for learning [35]. Among many kinds of ANNs, feed-forward ones are widely used by researchers who apply them as a tool for data classification or as a predicator. The idea of ANN usage is to create a learning set, which includes data characterized by input and output features. During training, ANNs create a model which is able to transform input features into output features of a data set. If the predicted or classified data depends on many variables (features), ANNs are a convenient tool for analyses.
- Case-based reasoning (CBR), in which the problem-solving method is focused on finding the solution in the base of examples (cases). The case which has been found will be adapted to the new usage. This method is applied when knowledge is presented as a description of cases.

Knowledge can take many forms, and it is necessary to identify the kind of knowledge representation method which is the most suitable for solving a particular problem.

In the presented customized product configuration QFD-KB, the following methods of knowledge representation were used [32]:

- Procedural knowledge used for identifying the product features recognized by the customer and identifying the product features recognized by the producer.
- Declarative knowledge applied to define the evaluation rules.
- Artificial neural network (ANN), used for assessing the missing manufacturing process parameters.
- Case-based reasoning (CBR), applied for identifying product alternatives.

The data and knowledge generated and used during manufacturing may be related to products, machines, processes, materials, inventories, maintenance, planning and control, assembly, logistics, performances, etc. [33].

http://dx.doi.org/10.5772/intechopen.79523

3.2. Algorithm of QFD-based knowledge base for product configuration

Enterprises develop data bases to store different types of data, e.g., data orders, codes of products, technical documentation related to products and the manufacturing processes, and product and process failure data.

Taking into consideration categories mentioned above, product configuration needs information related to customer requirements, product use circumstances, needed product characteristic analyzed from the functional point of view, product portfolio, parts characteristics, and manufacturing process characteristics.

The problem of determining product configuration can be structured according to the decision method presented in **Figure 3**. The presented approach developing web-based selection system was described by Gibson et al. [36].

Product configuration is divided into three levels including product-level configuration, component-level configuration, and manufacturing parameter-level configuration [37]. These three levels can be developed with the use of QFD series of matrices.

In the algorithm of QFD-KB for product configuration presented in **Figure 4** [32], the methods of knowledge representation such as rules from an expert, case-based reasoning and neural networks were applied.

Product offer preparation requires information regarding product portfolio offered by the enterprise and an evaluation of differences between customer requirements and the offered

Given: a set of products (configuration items) and processes.
Identify: a set of evaluation attributes, create scales, determine the importance and estimate missing product parameters.
Rate: Each alternative relative to each attribute.
Rank: Products (configuration items) from the most to the least promising.

Figure 3. A decision model for product configuration.

1. Identification of product characteristic.
2. Specification of target product characteristics, product decomposition, variants identification.
3. Variants evaluation, choosing the product to be redesigned.
4. Range of change identification, assessment of work time related to technical documentation preparation and the manufacturing process of the configured product.
5. Scheduling tasks related to product configuration, confirmation of product configuration.

Figure 4. Algorithm of QFD-KB for product configuration.

products. Customer service department staff should know how the product characteristics needed by the customer are different from the product characteristics offered by the enterprise and what kind of changes it is possible to implement in the product.

Product offer preparation needs a product requirement analysis, which includes analyzing product functions, reliability, safety, environment, packaging, transportation, storage, etc.

The decision problem solved with the use of QFD-KB for product configuration is how to choose and evaluate the right product from the product portfolio and adopt it to particular customer needs. The knowledge needed to solve this problem could origin from, e.g., experienced staff, databases, and documentation.

Possible data sources used in product configuration are presented in **Figure 5**.

3.2.1. Identification of product characteristics

Identification of customer requirements, product characteristics, their correlations and variant comparison were denoted with symbols presented in **Figure 6**, where a QFD scheme uses a square roof instead of a triangular roof matrix, as it is easier to use in a spreadsheet.

Configuration items should be determined according to the given criterion included in, e.g., [38]:

- Influence on functional and physical product characteristics determined by the client
- Innovatory character of product and process structure
- Safety of product usage
- Product reliability
- Logistic aspects

Identification of product characteristics from the customer point of view could be made in three stages.

The first stage regarding the category of requirements is related to product functions, which, in the case of toothed gear configuration, include, among others, torque transmission, weight of material handling and velocity of material handling.

The second stage regarding the category of requirements includes product environment conditions, e.g., environment temperature, dustiness, humidity, etc.

The third stage regarding category of requirements includes product trade characteristics, e.g., price, delivery time, warranty, etc.

3.2.2. Specification of target product characteristics, product decomposition and variant identification

To create a product, it is necessary to identify product features, quality level, packaging, etc. [37]. Accuracy and efficiency of product configuration depend on product structure used in product configuration.

Procedural knowledge helps to indicate the target value of configuration baseline which is needed for variant identification.

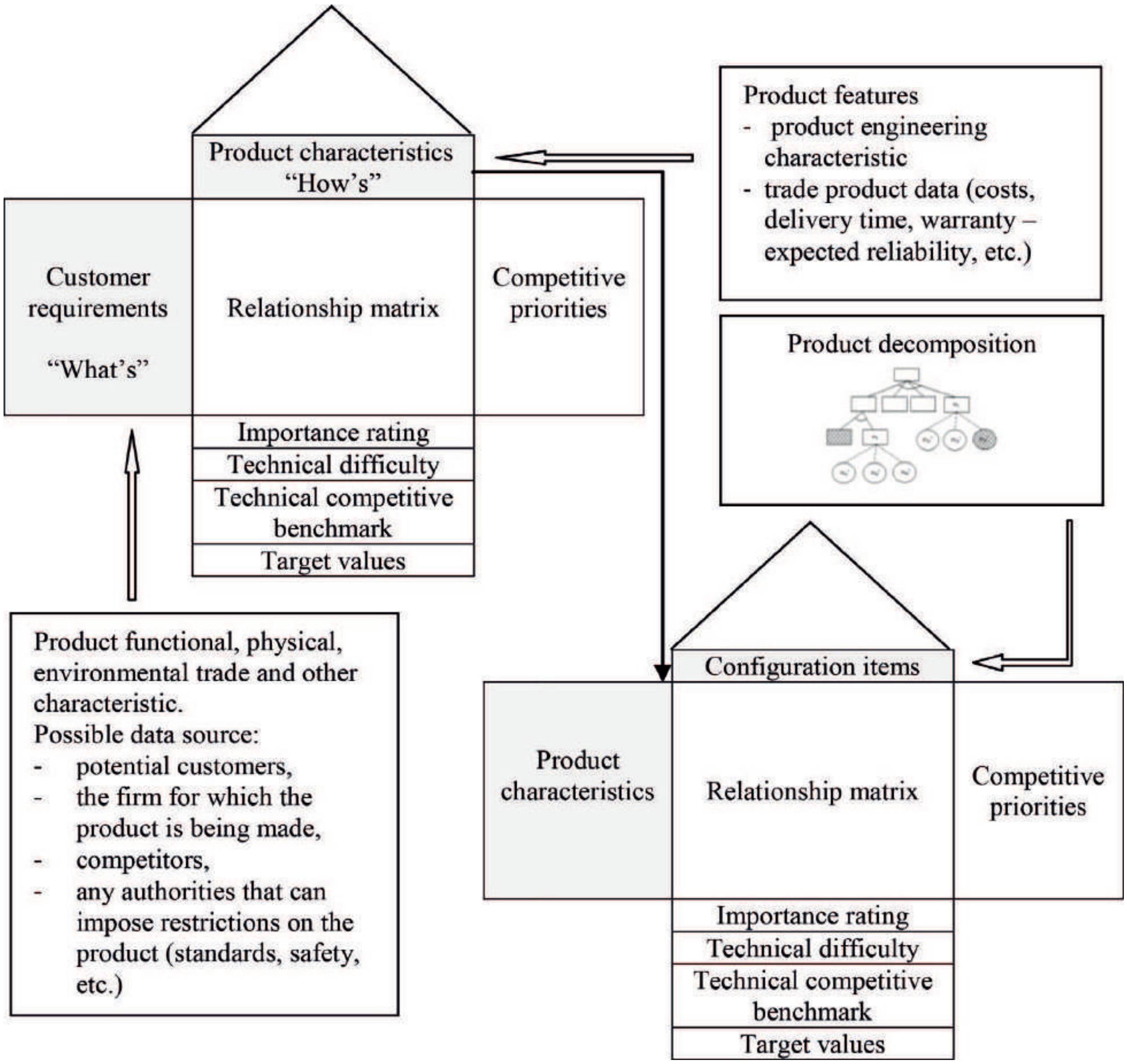


Figure 5. Product configuration data.

In the presented approach, decision rules were used to identify product alternatives. The premises in the proposed rules contain variation intervals of product features, where the conclusions include the proposed products (m_{zl}^{*}).

A general form of the rules is the following:

if $(p_{mk1t}^{wo1} - x_1) \le p_{mk1} \le (p_{mk1t}^{wo1} + x_1)$

and $(p_{mk2t}^{wo2} - x_2) \le p_{mk2} \le (p_{mk2t}^{wo2} + x_2)$

and ….

and $(p_{mkzt}^{woz} - x_z) \le p_{mkz} \le (p_{mkzt}^{woz} + x_z)$

then $m_k = m_{zl}^{*}$

where:

x_z—range of change, $z \in Z$,

p_{mkzt}^{woz}—target value of product characteristics, $z \in Z$,

p_{mkz}—product characteristics, $z \in Z$,

m_k—a configuration item, $k \in K$,

Z—a set of product characteristics,

K—a set of configuration items.

One of the important issues in product configuration is product decomposition, which provides the combination of components which gives a product suitable for a particular client. Product decomposition and functional requirements will help to answer the following question: which physical element(s) is responsible for the fulfillment of a specific functional requirement?

In literature we can find different approaches to product decomposition [39]. The presented method applies decomposition tree (**Figure 7**) [40], in which "and" nodes means that all components go together into product structure and "or" nodes mean that one of component alternatives should be put into product structure were used.

In product decomposition tree, there were distinguished standard components, and this one needs to be redesigned.

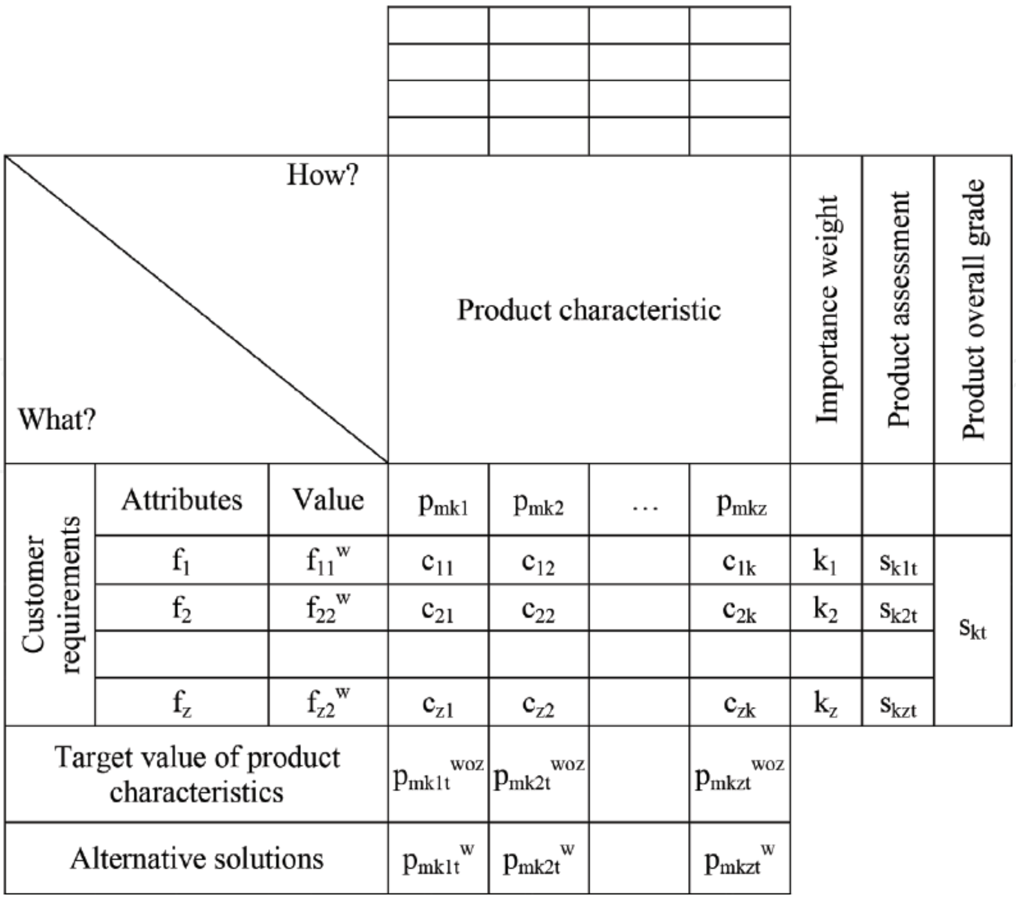


Figure 6. Product planning QFD matrix.

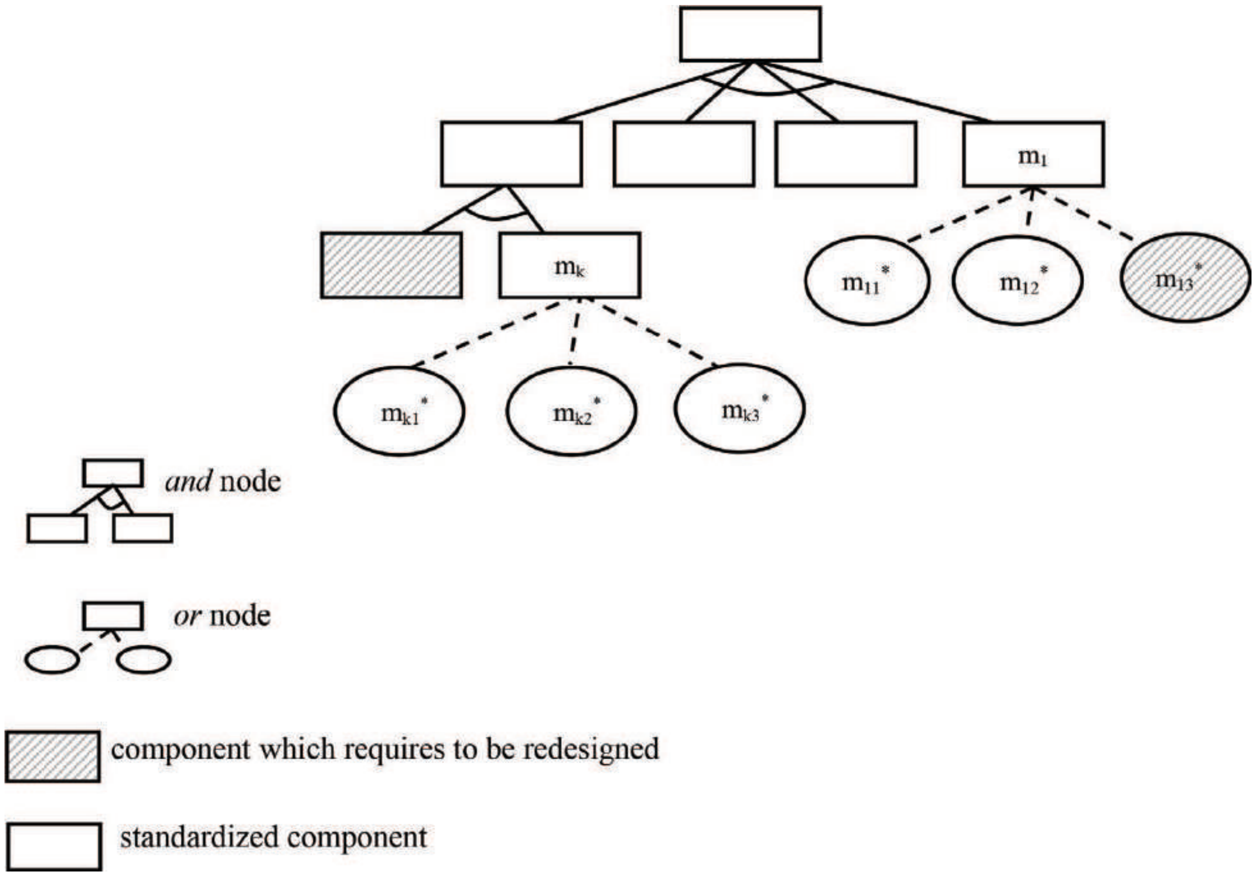


Figure 7. Product decomposition.

The identified configuration items, like product parts, components or modules should be described with the use of attributes and their values as appropriate specification with functional and physical characteristics (**Figure 8**).

Product decomposition in the product configuration process determines how detailed the product structure is. The presented product structures include alternative configuration items, which were characterized in **Table 1**.

3.2.3. Variant evaluation: choosing the product to be redesigned

Comparing product variants identifies the range of product change. The presented rank method applies an evaluation indicator calculated according to the formula (1):

$$w_{kzt} = \frac{\left|p_{mkzt}^{woz} - p_{mkzt}^{w}\right|}{p_{mkzt}^{woz}} \cdot 100 \tag{1}$$

where:

w_{kzt}—assessment indicator for product k, attribute z and variant t;

p_{mkzt}^{woz}—target level of product characteristic;

p_{mkzt}^{w}—offered attribute value.

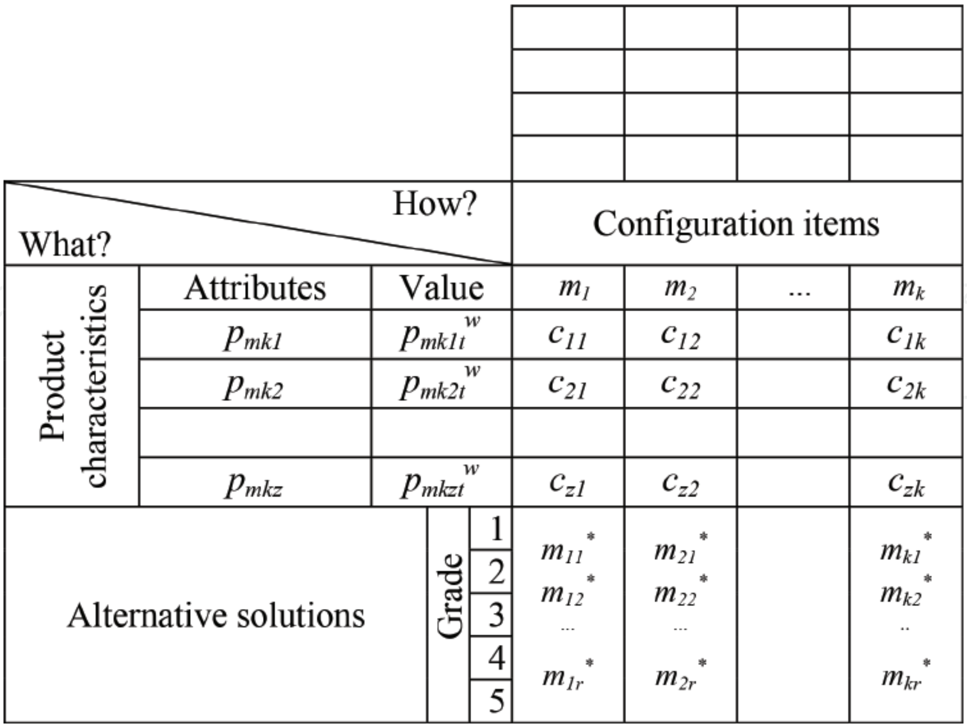


Figure 8. Configuration item planning QFD matrix.

Configuration items	**Alternatives**	**Attributes**			
		p_{mk1}	p_{mk2}	….	p_{mkz}
m_1	m_{11}^*	p_{m111}^w	p_{m121}^w	….	p_{mkz1}^w
	m_{12}^*	p_{m112}^w	p_{m122}^w	….	p_{mkz2}^w
	…	…	…	….	…
	m_{1l}^*	p_{m11t}^w	p_{m12t}^w	….	p_{mkzt}^w
m_2	m_{21}^*	p_{m2121}^w	p_{m221}^w	….	p_{mkz1}^w
	m_{22}^*	p_{m212}^w	p_{m222}^w	….	p_{mkz2}^w
	…	…	…	….	…
	m_{2l}^*	p_{m21t}^w	p_{m22t}^w	….	p_{mkzt}^w
….	….	….	….	….	….
m_k	m_{k1}^*	p_{mk11}^w	p_{m221}^w	….	p_{mkz1}^w
	m_{k2}^*	p_{mk12}^w	p_{m222}^w	….	p_{mkz2}^w
	…	…	…	….	…
	m_{kl}^*	p_{mk1t}^w	p_{m22t}^w	….	p_{mkzt}^w

Table 1. Configuration item variants.

Evaluation of product variant could be determined with the use of the rules presented in **Table 2** and the Eq. (2) [45]:

$$s_{kt} = \frac{\sum_z s_{kzt} \cdot k_z}{z} \tag{2}$$

http://dx.doi.org/10.5772/intechopen.79523

$$s_{kt} \in \{1, 2, 3, 4, 5\}$$

$$k_z \in N$$

where:

s_{kt}—overall grade assessment of fulfilling requirements for variant t and configuration item k.

s_{kzt}—assessment grade of fulfilling requirements for variant t and configuration item k.

k_z—importance weight of attribute *z.*

Product alternative evaluation uses assumptions of the CBR method and decision rules which help to evaluate the presented solutions.

It could happen that the selected product is not suitable for a particular client. In such a case, it is necessary to assess the range of change in the product and the manufacturing process, which helps to determine the trade data related to the configured product.

The presented approach helps to identify the importance of product attribute and compares product components. The assessment of product components helps to choose the proper component variant or the variant which needs to be redesigned.

The presented approach is useful in supporting decisions during product configuration. The results of overall product assessment are given in the bottom part of a QFD matrix (**Figure 8**) [41].

3.2.4. Range of change identification, assessment of work time related to technical documentation preparation and the manufacturing process of the configured product

Changes in a redesigned product are focused on product structure and adapting the manufacturing process to allow to, e.g., fulfill a new function, reduce delivery time and reduce costs.

Assessment indicator		Assessment grade	
if	$w_{kzt} \le o_{1z}$	then	$s_{kzt}=5$
	$o_{1z} < w_{kzt} \le o_{2z}$		$s_{kzt}=4$
	$o_{2z} < w_{kzt} \le o_{3z}$		$s_{kzt}=3$
	$o_{3z} < w_{kzt} \le o_{4z}$		$s_{kzt}=2$
	$o_{4z} < w_{kzt}$		$s_{kzt}=1$
Where $o_{1z}, o_{2z}, \ldots, o_{4z}$ – bottom and upper values of parameter w_{kzt}			

Table 2. Assessment rules.

Product customization takes time needed to product redesign and manufacturing. Work time of specified tasks related to product development and manufacturing is one of the most important criteria which contribute to offer attractiveness. Delivery time could be assessed based on work time of product technical documentation and the manufacturing standard preparation.

Work time can be estimated with the use of work measurement methods which determine the length of time to complete a given task.

Work measurement methods include:

- Synthesis and analytical estimation (in this method it is necessary to break down the tasks into elements).
- Analytical estimation (the time required to complete a task is build up from synthetic data).
- Time study (the time of manufacturing tasks is measured).
- A method based on artificial intelligence [42–44]. In case of product redesign, missing data can be estimated with the use of ANN [46, 47].

Work time estimation of the manufacturing process needs the process structure and planning parameters.

3.2.5. Scheduling tasks related to product configuration: confirmation of product configuration

Scheduling the tasks to redesign product is focused on fixing the project deadline. For that purpose methods such as Gantt chart, PERT, CPM and GERT can be used.

Gantt chart is a type of bare chart which illustrates project task order in function of time; duration of each activity is shown.

Another approach presented network-based methods such as PERT, CPM and GERT.

Project evaluation and review technique (PERT) is focused on analyzing tasks involved in the project and enabled fixing the minimum time needed to complete the project. This method uses probabilistic duration of project tasks.

Critical path method (CPM) is a method which calculates the longest path in the project task network, fixing the shortest time to complete the project with the use of deterministic duration of project tasks.

Graphical evaluation and review technique (GERT) use both probabilistic network and probabilistic estimation of project task duration.

3.3. QFD-KB supporting configuration of a motoreducer

An example presents a configuration of a motoreducer used as a feeder device driving gear. Based on the algorithm presented in **Figure 4**, the evaluation of product configuration items was developed.

http://dx.doi.org/10.5772/intechopen.79523

The first stage of the algorithm was focused on definition of feeder device driving gear characteristic which was placed on the left part of QFD matrix (**Figure 9**).

In the second stage of the algorithm, target motoreducer characteristics were specified and entered to the bottom row in the QFD matrix.

The next stage of product configuration is concerned with identifying the product structure and product decomposition and selecting the configuration items (**Figure 10**). A too detailed product decomposition causes costs, but rough product decomposition causes risk related to product characteristic failure.

Characteristics of configuration item (components, modules, parts) alternatives of feeder device driving gear are presented in **Table 3**.

An example of w_{kzt} coefficient calculation and s_{kzt} grade determination for configuration items of feeder device driving gear was presented in **Tables 4** and **5**. Assessment of configuration items alternatives used the rules presented in **Table 6**.

A comparison of configuration item alternatives is presented in **Figure 11**.

The range of change in product structure depends on, among others, the type of function introduced to the product. In the case of a motoreducer, product function can include, e.g., enabling assembly in a particular workplace, transmitting torque, etc. Changes on functions related to product assembly in a particular workplace can, for example, be focused on changing output shaft diameter.

	4				
	3	+	+		
	2			+	
	1			+	
What?	How?	Nominal power	Output speed	Ratio	…..
Attribute	Value	1	2	3	
Belt with	1200				
Belt speed	3		9	9	
Power	30	9			
….					
Needed delivery time	5				
Target value		30	108	14	

Figure 9. Attribute target value of feeder device driving gear.

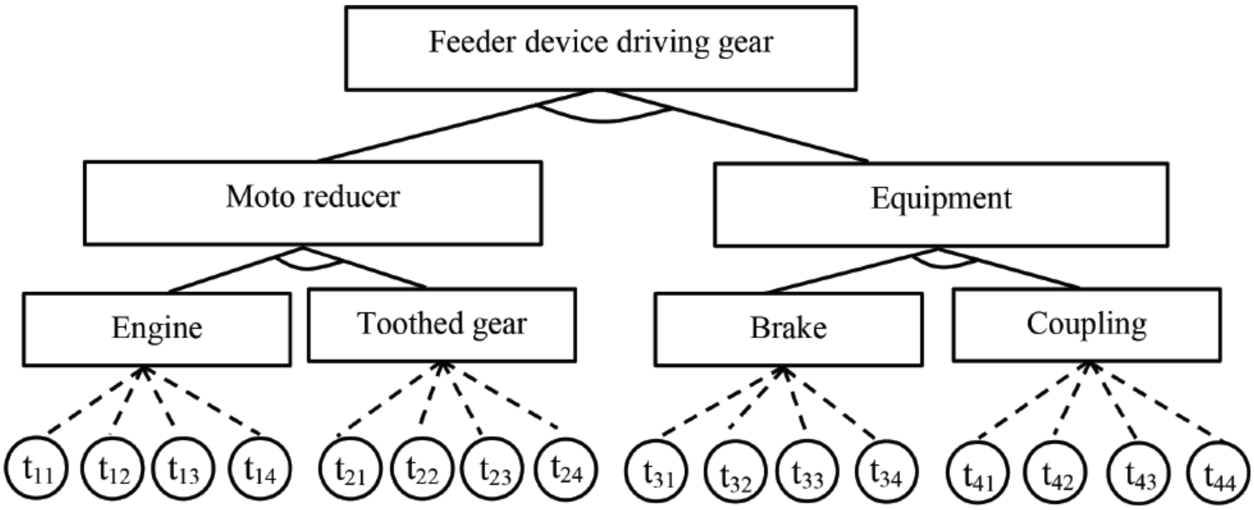


Figure 10. Feeder device driving gear structure.

Configuration items	Alternatives	Attributes		
		Power	Speed	Ratio
Toothed gear	t_{11}	33	83	18
	t_{12}	32	50	20
	t_{13}	33	94	16
	t_{14}	35	56	18
Engine	t_{21}	30		
	t_{22}	35		
	t_{23}	40		
	t_{24}	35		

Table 3. Feeder device driving gear—Configuration item alternative characteristics.

Configuration items	Alternatives	Attributes w_{kzt} coefficient calculation					
		Power	w_{k1}	Speed	w_{k2}	Ratio	w_{k3}
Toothed gear	t_{11}	33	10,00	83	23,15	18	28,57
	t_{12}	32	6,67	50	53,70	20	42,86
	t_{13}	33	10,00	94	12,96	16	14,29
	t_{14}	35	16,67	56	48,15	18	28,57
Engine	t_{21}	30	0,00				
	t_{22}	35	16,67				
	t_{23}	40	33,33				
	t_{24}	35	16,67				

Table 4. Configuration items—Indicator of w_{kzt} calculation.

Configuration items	Alternatives	Attributes grade						
		Power	Grade	Output speed	Grade	Ratio	Grade	Overall grade
Toothed gear	t_{11}	33	4	83	2	18	2	2,67
	t_{12}	32	4	50	1	20	2	2,33
	t_{13}	33	4	94	3	16	3	3,33
	t_{14}	35	3	56	2	18	2	2,33
Engine	t_{21}	30	5					5
	t_{22}	35	3					3
	t_{23}	40	2					2
	t_{24}	35	3					3

Table 5. Configuration item variants, partial assessment s_{kzt}.

	Assessment indicator		Assessment grade
If	$w_{kzt} \leq 5$	Then	$s_{kzt} = 5$
	$5 < w_{kzt} \leq 10$		$s_{kzt} = 4$
	$10 < w_{kzt} \leq 20$		$s_{kzt} = 3$
	$20 < w_{kzt} \leq 50$		$s_{kzt} = 2$
	$50 < w_{kzt}$		$s_{kzt} = 1$

Table 6. An example of assessment rules.

What? / How?			Toothed gear	Engine
Attribute	Value		1	2
Power	30		9	3
Output speed	108		9	
Ratio	14		9	
....				
Delivery time	5 week			
	Grade	1		
		2		t_{23}
		3	t_{11}, t_{12}, t_{13}, t_{14}	t_{22}, t_{24}
		4		
		5		t_{21}

Figure 11. Configuration item assessment in QFD matrix.

The presented product configuration algorithm helps to identify product attributes and compare and select product components. It is based on the following assumptions [32]:

- The product can be divided into configuration items which are components, modules or parts with a modular structure.
- There exist some alternatives of the configuration items.
- Enterprise staff is experienced in product adaptation according to individual customer requirements.

4. Conclusions

In basic applications QFD uses human knowledge. The presented approach is focused on developing a QFD-KB knowledge base, which is able to support human decisions related to product configuration. The presented algorithm joins methods of knowledge representation and supports decisions related to identifying and assessing product configuration items, such as components, modules and parts. In the presented QFD-KB, attributes analyzed by customer and producer are related to one another with the QFD matrix.

Methods of knowledge representation, such as procedures, rules, ANN and CBR are useful in the presented QFD-KB. The presented approach uses advantages and avoids disadvantages of different methods of knowledge representation. Selection of the proper knowledge representation method determines the effectiveness of QFD-KB.

Integration of the knowledge related to customer requirements, product structure and the manufacturing process helps to assess product characteristics in make-to-order product offer preparation.

The proposed algorithm of product configuration uses the QFD method and performs comparison and evaluation of configuration item variants, as well as missing data estimation related to the production process of product redesign.

Product configuration requires knowledge related to, among others, product structure, manufacturing process and potential failure problems.

Product configuration efforts are focused on the following categories:

- Collection of rules related to product selection and redesign
- Collection of facts about products functions and their structure
- Collection of facts and rules regarding product manufacturing variants, possible failures, timing and costing

The decision process regarding product configuration, which is focused on compatibility between customer requirements and functional and physical product features, can be supported with the use of QFD-KB for product configuration.

Conflict of interest

There is no conflict of interest.

Author details

Izabela Kutschenreiter-Praszkiewicz

Address all correspondence to: ipraszkiewicz@ath.bielsko.pl

University of Bielsko-Biala, Bielsko-Biała, Poland

References

[1] Jiao J, Ma Q, Tseng MM. Towards High Value-Added Products and Services: Mass Customisation and Beyond. Vol. 23. Amsterdam: Elsevier, Technovation, The International Journal of Technological Innovation, Entrepreneurship and Technology Management; 2003. pp. 809-821

[2] Rong YK. Setup planning and tolerance analysis. In: Wang L, Shen W, editors. Process Planning and Scheduling for Distributed Manufacturing. Springer Series in Advanced Manufacturing. London: Springer; 2007. pp. 137-166

[3] Saaksvuori A, Immonen A. Product Lifecycle Management. Berlin Heidelberg: Springer; 2005

[4] Ameri F, Dutta D. Product Lifecycle Management Needs, Concepts and Components. Ann Arbor: University of Michigan; 2004

[5] Liu W, Zeng Y. Conceptual Modeling of design chain management towards product lifecycle management. In: Chou SY, Trappey A, Pokojski J, Smith S, editors. Global Perspective for Competitive Enterprise, Economy and Ecology. Advanced Concurrent Engineering. London: Springer; 2009. pp. 137-148

[6] Jinsong Z, Qifu W, Li W, Yifang Z. Configuration-oriented product modelling and knowledge management or made-to-order manufacturing enterprises. The International Journal of Advanced Manufacturing Technology. 2005;**25**:41-52

[7] Hu SJ, Ko J, Weyand L, ElMaraghy HA, Lien TK, Koren Y, Chryssolouris G, Nasr N, Shpitalni M. Assembly system design and operations for product variety. CIRP Annals Manufacturing Technology. 2011;**60**:715-733

[8] Sanchez R. Building real modularity competence in automotive design, development, production, and after-service. International Journal of Automotive Technology and Management. 2013;**13**:204-236

[9] Stone R, Wood K, Crawford R. A heuristic method for identifying modules for product architectures. Design Studies. 2000;**21**:5-31

[10] Kubota F, Hsuan J, Cauchick-Miguel P. Theoretical analysis of the relationships between modularity in design and modularity in production. International Journal of Advanced Manufacturing Technology. 2017;**89**:1943-1958

[11] Koren Y, Hu S, Gu P, Shpitalni M. Open-architecture products. CIRP Annals-Manufacturing Technology. 2013;**62**(2):719-729

[12] Ma H, Peng Q, Zhang J, Gu P. Assembly sequence planning for open-architecture products. International Journal of Advanced Manufacturing Technology. 2018;**94**:1551-1564

[13] Su Y. Product family Modeling and optimization driven by customer requirements. In: Hinduja S, Li L, editors. Proceedings of the 36th International MATADOR Conference. London: Springer; 2010

[14] ElMaraghy H, Azab A, Schuh G, Pulz C. Managing variations in products, processes and manufacturing systems. CIRP Annals–Manufacturing Technology. 2009;**58**:441-446

[15] Kannan M, Saha J. A feature-based generic setup planning for configuration synthesis of reconfigurable machine tools. International Journal of Advanced Manufacturing Technology. 2009;**43**:994-1009

[16] Nurcahya E. Configuration instead of new design using reference product structures. In: Krause FL, editor. The Future of Product Development. Berlin, Heidelberg: Springer; 2007

[17] Mehrabi M, Ulsoy A, Koren Y. Reconfigurable manufacturing systems and their enabling technologies. International Journal of Manufacturing Technology Manage. 2000; **1**(1):113-130

[18] Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: Principles, design, and future trends. Frontiers of Mechanical Engineering. 2018;**13**:121-136

[19] Deif A, ElMaraghy W, Systematic Design A. Approach for reconfigurable manufacturing systems. In: ElMaraghy HA, ElMaraghy WH, editors. Advances in Design. Springer Series in Advanced Manufacturing. London: Springer; 2006

[20] Tigane S, Kahloul L, Bourekkache S. Reconfigurable stochastic petri nets for reconfigurable manufacturing systems. In: Borangiu T, Trentesaux D, Thomas A, Leitão P, Oliveira J, editors. Service Orientation in Holonic and Multi-Agent Manufacturing. Studies in Computational Intelligence. Vol. 694. Cham: Springer; 2017

[21] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Van Brusse H. Reconfigurable manufacturing systems. Annals of the CIRP. 1999;**48**(2):527-540

[22] Akao Y.: Development History of Quality Function Deployment. The Customer Driven Approach to Quality Planning and Deployment. Minato, Tokyo: Asian Productivity Organization; 1994

[23] Barad M. Quality function deployment (QFD). In: Strategies and Techniques for Quality and Flexibility. Springer Briefs in Applied Sciences and Technology. Cham: Springer. p. 2018

[24] Revelle J. Quality Essentials: A Reference Guide from A to Z. ASQ Quality Press: Milwaukee; 2004. pp. 152-155

[25] Iranmanesh H, Thomson V. Competitive advantage by adjusting design characteristics to satisfy cost targets. International Journal of Production Economics. 2008;**115**:64-71

[26] Kutschenreiter-Praszkiewicz I. Integration of product design and manufacturing with the use of artificial intelligent methods. Journal of Machine Engineering. Wrocław. 2011;**11**(1-2):46-53

[27] Raharjo H, Brombacher AC, Xie M. Dealing with subjectivity in early product design phase: A systematic approach to exploit quality function deployment potentials. Computers and Industrial Engineering. 2008;**55**:253-278

[28] Raissi S, Izadi M, Saati S. Prioritizing engineering characteristic in QFD using fuzzy common set of weight. American Journal of Scientific Research. 2012;**49**:34-49

[29] Kamrani A, Salhieh S. A decomposition methodology for uncoupled modular product design. In: Mass Customization. Boston, MA: Springer; 2004

[30] Yan L, Shujuan L, Shaokun W. A virtual product family to support design for customers. In: Yan X-T et al., editors. Perspectives from Europe and Asia on Engineering Design and Manufacture. New York: Springer Science+Business Media; 2004

[31] Kutschenreiter-Praszkiewicz I. Knowledge representation in the knowledge-based product configuration method. Journal of the University of Applied Sciences Mittweida. 2012;**3**:39-42

[32] Kutschenreiter-Praszkiewicz I. Application of knowledge based systems in technical preparation of machine parts production. Advances in Manufacturing Science and Technology. 2013;**37**(1):19-29

[33] Choudhary AK, Harding JA, Tiwari MK. Data mining in manufacturing: A review based on the kind of knowledge. Journal of Intelligent Manufacturing. 2009;**20**:501-521

[34] Traczyk W, Wierzbicki A, Huynh V. Knowledge representation and multiple criteria aggregation. Studies in Computational Intelligence (SCI). 2007;**59**:281-320

[35] Pole D, Mackworth A. Artificial Intelligence. New York: Cambridge University Press; 2010

[36] Gibson I, Rosen D, Strucker B. Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing. Springer; 2010

[37] Zhu B, Wang Z, Yang H, Mo R, Zhao Y. Applying fuzzy multiple attributes decision making for product configuration. Journal of Intelligent Manufacturing. 2008;**19**:591-598

[38] Pokora W, Szkoda J, Świderski A. Zarządzanie konfiguracją wymagania NATO(AQUAP). Problemy Jakości. 2006;**8**:16-20

[39] Yadav O, Singh N, Goel P. Reliability demonstration test planning: A three dimensional consideration. Reliability Engineering and System Safety. 2006;**91**:882-893

[40] Jiao J, Tseng M, Dufty V, Lin F. Product family modeling for mass customization. Computers and Industrial Engineering. 1998;**35**(34):495-498

[41] Kutschenreiter-Praszkiewicz I. Systemy bazujące na wiedzy w technicznym przygotowaniu produkcji części maszyn. Bielsko-Biała: Wydawnictwo Naukowe Akademii Techniczno-Humanistycznej; 2012

[42] Xu D, Yan H-S. An intelligent estimation method for product design time. International Journal of Advanced Manufacturing Technology. 2006;**30**:601-613

[43] Pasternak K. Zarys zarządzania produkcją. PWE: Warszawa; 2005

[44] Kutschenreiter-Praszkiewicz I. Wykorzystanie sztucznych sieci neuronowych do prognozowania czasu projektowania przekładni zębatych w warunkach niepewności i ryzyka. Archiwum Technologii Maszyn i Automatyzacji. 2007;**27**(2):113-120

[45] Kutschenreiter-Praszkiewicz I. Planowanie procesu produkcyjnego wyrobu innowacyjnego / Production process planning of innovative product. PAR: Pomiary, Automatyka, Robotyka. 2015;**1**:57-64

[46] Kutschenreiter-Praszkiewicz I. Application of neural network in QFD matrix. Journal of Intelligent Manufacturing. 2013;**24**(2):397-404

[47] Kutschenreiter-Praszkiewicz I. Application of artificial neural network for determination of standard time in machining. Journal of Intelligent Manufacturing. 2008;**19**(2):233-240

Chapter 5

Testing and PLM: Connecting Process and Product Models in Product Development

Khadija Tahera and Christopher Earl

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80364

Abstract

The product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from the idea generation, through the design, development and manufacturing to service and disposal of the product. Testing often is considered to be an activity to perform during the product design and development phase. However, the information about how a product is designed and tested is useful for designing the maintenance and the monitoring and maintenance data can provide useful information in developing the next generation of a new product. The main objective of this chapter is to understand how testing process in integrated into the product lifecycle. This chapter reports a case study in a UK based manufacturing company and based on that develops a framework to highlight the importance of testing. Also, proposes a conceptual model of how testing activities can be managed in the product lifecycle management process.

Keywords: product development process, testing, computer aided engineering (CAE) analysis, design for maintenance, product description

1. Introduction

During a product development process, information becomes available to, and is requested by, many partners, design teams and organisations. Information about properties and performance of components and subsystems is the basis of decisions made in the development process. This information has many sources ranging from mathematical models, simulations, testing of physical models and prototypes and customer use data. It has many destinations, in the primary design phase and then through the product life in operations of maintenance, refit and redesign. Product Lifecycle Management (PLM) is primarily concerned to create product models to cover the full range of processes, operations and activities required to support a product through its lifecycle. A critical and current issue is the extent that these product models provide the basis for generating corresponding process models particularly dynamically so that process models continuously reflect the current state of the product models [1]. One aim is to enhance through improvements in workflow for planning product development processes, the significant gains that PLM systems have delivered over a period of 25 years in reducing both the duration and costs of product development [2]. Research by the authors [3, 4] has concentrated on the processes of testing and their ubiquity through product development. Critical testing processes such as field testing ([2], for example) are identified in these workflows, which deliver product development. However, the way that these testing processes form a critical part of all the processes from start to finish of the product lifecycle, whether as inputs, as drivers for iteration, for establishing alignment to regulations or for confirmation of completion of a satisfactory design, has received limited consideration in the literature. Tests are long and expensive activities and most product development activities and tasks depend on the results of test, whether, physical test, simulations or field data gathered during customer operations. This chapter examines methods to integrate testing more closely with other product development processes as well as to improve the planning of the processes of testing so that testing activities are scheduled optimally. Further, the chapter examines how the results of tests can be applied to assist other product development processes. Critically, it analyses how preliminary test results can be of significant assistance to these other processes, speeding their completion.

Previous research by the authors has addressed two particular issues. First, combining information from both physical and virtual testing (simulation) can bring forward in time the availability of a workable product model suitable for the next design stage [3]. This helps planning a design process in an iterative cycle of proposal, test and redesign through developing a method to analyse the overlap between steps in this cycle and optimise this overlap to reduce overall development time. In particular, the long duration of some physical tests, which are necessary to ensure performance and conformance to regulations and standards, are a bottleneck in product development. Starting downstream design activities dependent on these tests before the tests are completed can ease this bottleneck. Essentially, the proposed method applies information from two distinct product models, simulation and physical test to change the process model, allowing significant overlap between activities. The method relies on observing the degree of convergence between simulation and test data.

The second piece of research [4, 5] examines more closely how testing activities can be explicitly integrated into the product development process for complex engineering products. This research highlights the mismatch between several models of product development which tend to relegate testing to be an activity late in the design process or primarily concerned with quality issues. In fact, examination of practice shows that testing is integrated throughout. The misconception in product development process models has possibly arisen because the long duration of physical tests means that the results of testing are not available until later stages, although the activity itself necessarily starts early in the process. This research therefore points to a significant reappraisal of appropriate process models resulting from how data is available in product models. Both strands of previous research have focused on testing for design, rather than wider product development through lifecycle. However, they provide useful insights into the relationship between the product models of PLM [1, 2] and the process models [6] in product development.

This chapter applies the results of this research to integrate testing and design more widely in the product lifecycle. Section 2 introduces some background and literature of PLM with particular reference to testing. Testing is considered from a general perspective as activities which analyse properties and performance of designs. A short review of existing research on the relationship between testing and PLM in Section 3 covers the mixes of testing activities at various stages of the product lifecycle based on some industry observations. Section 4 extends the proposition, first proposed by Tahera et al. [3] for testing and design, and reviews a three-way mix of testing types comprising simulation, use data (from embedded product monitoring) and physical testing. Further, wider implications of these methods are drawn in Section 5, especially in how PLM systems coordinate product models generated through design, testing and product monitoring activities. Section 6 discusses the tentative nature of these findings, the requirements for further research and the potential benefits for PLM systems. In particular, the refinements in process models recognise testing activities explicitly and their close integration with other processes in product development. Changes in process models drive changes to product models and PLM. This research does not cover the latter stages [as referred as End of life (EOL)] of product lifecycle.

2. PLM data and descriptions

Two observations are relevant when considering testing in product lifecycle. First, testing is a continuing activity, whether physical or virtual, throughout lifecycle. Testing data sets up maintenance schedules and product use data assists in updating these schedules. Periodic refit and redesign may emerge from testing new materials, components and subsystems to track upgrades and changes to customer requirements.

Second, testing supplies information which becomes part of a product description. PLM systems handle several product descriptions [7, 8] and a major challenge is maintaining consistency and integrity of multiple descriptions In the simple case this might mean ensuring that changes to a design in one description, perhaps CAD geometry, are propagated accurately to descriptions for manufacture and assembly such as BoMs and tolerancing schemes. Results of testing update these multiple descriptions in PLM systems. As observed above, testing takes place continuously through product development and product use. However, the schedules for physical testing activities have long duration.

Product performance data is gathered over a range of use conditions and longitudinally over time. Data of two types is relevant in testing. Special tests can be set to investigate particular characteristics such as thermal dynamics of an engine which formed one of the areas of previous research [3]. Other data is gathered from product monitoring in the field. Increasingly the latter data, which may include component wear, degradation in performance or replacement of components, for determining preventative maintenance or redesign of failing components, is well established for complex products such as aerospace [9]. However, quick and effective use of this testing data depends on levels of confidence when only partial data is available. A similar situation to testing in the initial stages [3] occurs throughout lifecycle, where reliable decisions on maintenance, retrofit and redesign when taken early can reduce operational product cost to customers as well as more speedily remove potential causes of failure.

The broader challenge for PLM systems with their multiple decisions of different aspects of a product is two-fold. **Figure 1** indicates these two broad challenges as updating performance and product descriptions iteratively. The first is to ensure that testing data updates performance and operational user descriptions consistently. The second occurs, when testing or use monitoring data prompts component or subsystem redesign. The underlying configurational product descriptions such as (Bill of materials) BoMs for manufacture and assembly will change accordingly, and updating these new product descriptions consistently is critical. With the focus of this chapter on the interplay of simulations, physical testing and monitoring data, it is noted that simulations depend on design descriptions and that inconsistent descriptions will reduce the accuracy of simulations leading to slower alignment between the results of simulations and the results from physical test. PLM has a design focused view in which the processes of product development effectively 'call for' testing and monitoring to validate and verify a design proposal. A critical circumstance in product lifecycle is the incorporation of new technologies in components and systems. Testing is often mandatory to meet regulations before new components can be fitted and operated, especially for complex products in the automotive and aerospace sectors which have a long service life. Conversely it is suggested here that a testing and use data view of PLM can drive design. It is argued that testing and design are equal partners in the product development process and promoting closer integration through PLM will give competitive advantage. This chapter explores how product development teams can reduce redesign iteration cycle time at several points in the product lifecycle. Incremental reductions in product cost and improvements in customer service at each cycle accumulate as the number of cycles increases yielding a significant benefits over the whole lifecycle.

Several pieces of research have examined how early availability of data from testing can reduce overall design duration [10–12]. However, these methods generally take an abstract perspective looking at optimising a given set of design and testing activities. However, they do not

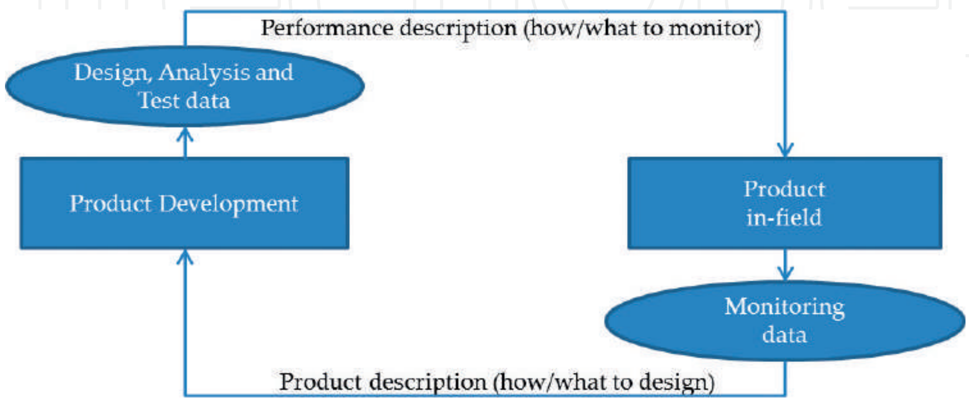


Figure 1. Iterative updating of product and performance descriptions.

really question the assumed relationship between design (generally interventions in product such as design, maintenance or retrofit) and testing (generally derived data from analysis, simulation, physical test, or product use monitoring). Previous research [3] has examined the relationship between design and testing in their narrow senses and concluded that rebalancing leads to a more feasible and realistic model of process. Data from testing (in the wider sense throughout lifecycle) is expensive and time consuming to provide. How and when it is used is a critical part of process models. Conversely these descriptions of performance and functionality derived from testing require support from PLM alongside descriptions of product components, configurations and architectures derived from design activities [13].

Dynamic process models have been identified as critical to delivering the benefits of PLM systems [1, 14]. Methods to construct evolving process models from PLM product models use Design Structure Matrices and workflow networks. This research theme presents a new framework for PLM systems so that they can support these evolving process models. Conversely, process models which highlight the balance (and integration) of design and testing (in their wider senses outlined above) assist in the construction of product models in PLM systems.

Figure 2 presents a generic sequential process model [1] of the stages of a product's lifecycle from identifying market needs to recycling. This also represents the overall information flows in product lifecycle.

Another view of information flow within product lifecycle is presented in **Figure 3** adopted from [15], which consists of three main phases: beginning of life (BOL) includes idea generation, product development and production, middle of life (MOL), includes use, service and maintenance and end of life (EOL) comprises of reuse, recycle and disposal.

At every stage of the product lifecycle, information such as design specification, Computer Aided Design (CAD) drawings, Computer aided Engineering (CAE), physical test results and technical documents are generated [16]. These pieces of information are captured, stored, managed, and transferred between different people and application system during product lifecycle management. In general, PLM includes the planning, execution, control, and documentation of all processes in the product lifecycle [17]. Information flow from the BOL phase to other phases is managed through several information systems, such CAD tools, product data management (PDM) and knowledge management (KM). However, the information flow from/to MOL and EOL is not well supported or managed through current tools and information systems, therefore the critical information from these phases about product use data often do not adequately feedback to the BOL phase [17]. This may cause the decision- making process in the product lifecycle to be inaccurate and incomplete.

Different descriptions make up a product model in PLM. These are created during stages of the product lifecycle to facilitate the next stage of the process. The descriptions of product,

Figure 2. Development process model (taken from [1]).

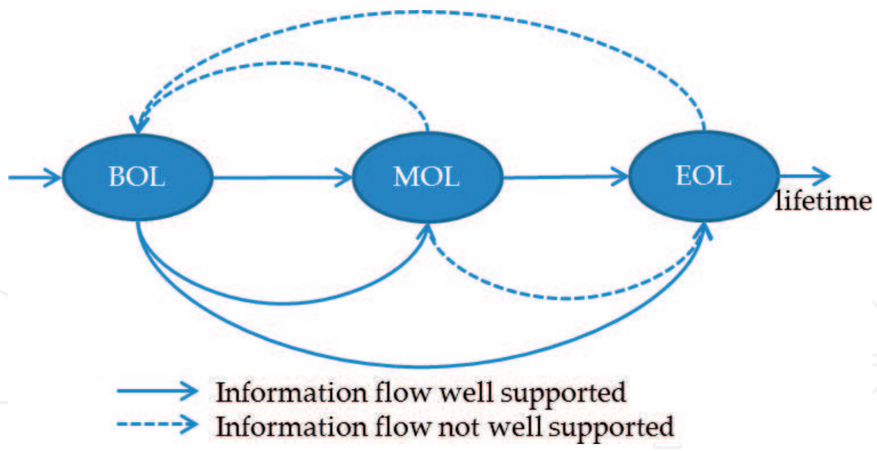


Figure 3. Levels of information flow achieved between the different product lifecycle phases [15].

design and performance are particularly relevant for PLM management. The definitions for these descriptions vary and for this research the following definitions are adopted.

Product description is the explicit result of a design process, which is the information for defining the product [18] usually in the form of drawings and CAD models. Design information is of two types. First, background information, such as the design requirements, design methods and design standards and second foreground information on the details of the product. The latter is the product description. *Design description* covers the information from which the product can be manufactured [19]. *Performance description* is the realistic system-level performance description. This can be based on several different physical models. For example, heterogeneous models covering mechanical, fluid and electronic dimensions are needed to describe the performance of complex products [20].

3. Testing across product lifecycle: an industry example

This section outlines testing and associated activities at various stages of the product lifecycle as observed in a major international company which designs and manufactures automotive diesel engines. First, the company-based product lifecycle management process model is described. Next, types and sequencing of testing in the product development process of the company is examined. The scope of testing is then broadened to include other aspects of PLM, especially maintenance and new generation product design.

It is a UK based diesel engine design and manufacturing company, that offers a wide range of diesel and gas engines and power packages from 8.2 kW to 1886 kW and has the capacity to produce up to 800,000 units per year. There are product families with different power ranges to meet the requirements from different markets. Products also vary in families depending on the number of cylinders, aspiration and control mechanism. **Figure 4** shows the series of engines in the company's product range. Eighteen semi-structured interviews were carried out at the company premises from February 2011 to February 2014. Eight engineers including a senior engineer, a development engineer, a business manager, a verification and validation

http://dx.doi.org/10.5772/intechopen.80364

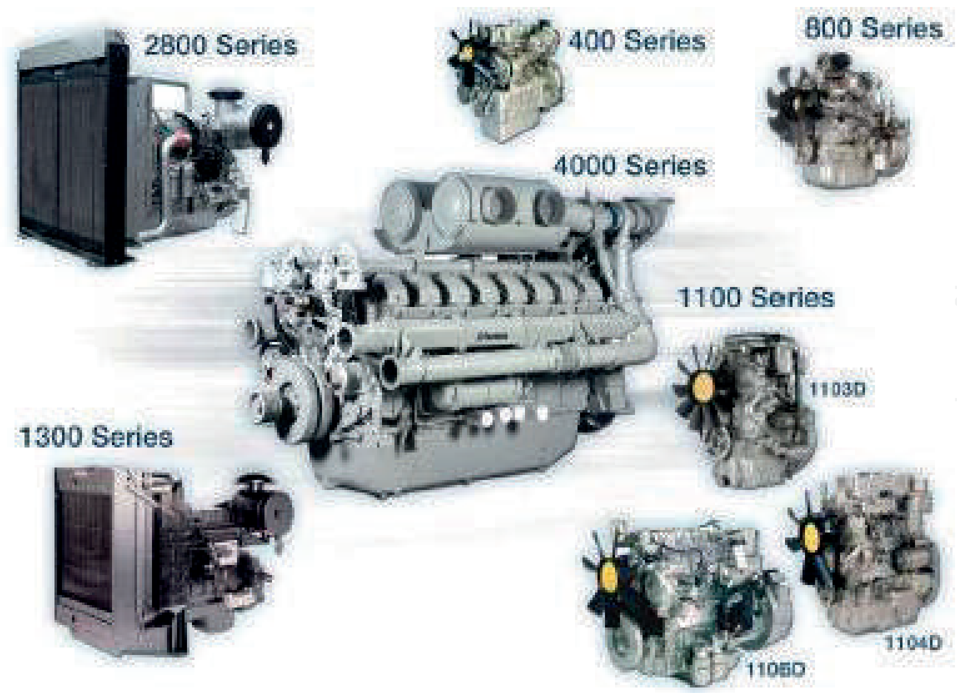


Figure 4. Company's product range (taken from [4]).

manager and a validation team leader were interviewed. The case studies involved a series of interviews ranging from 40 to 180 minutes in duration.

Figure 5 presents the view of the diesel engine company on their product lifecycle management process model. The top layer of the model shows key stages of the product lifecycle from the business strategy to the disposal of the product. The beginning, middle and end of life (BOL, MOL, EOL) classification, introduced in Section 2, is shown on the bottom layer. The middle layers show key activities that are undertaken during the stages of product

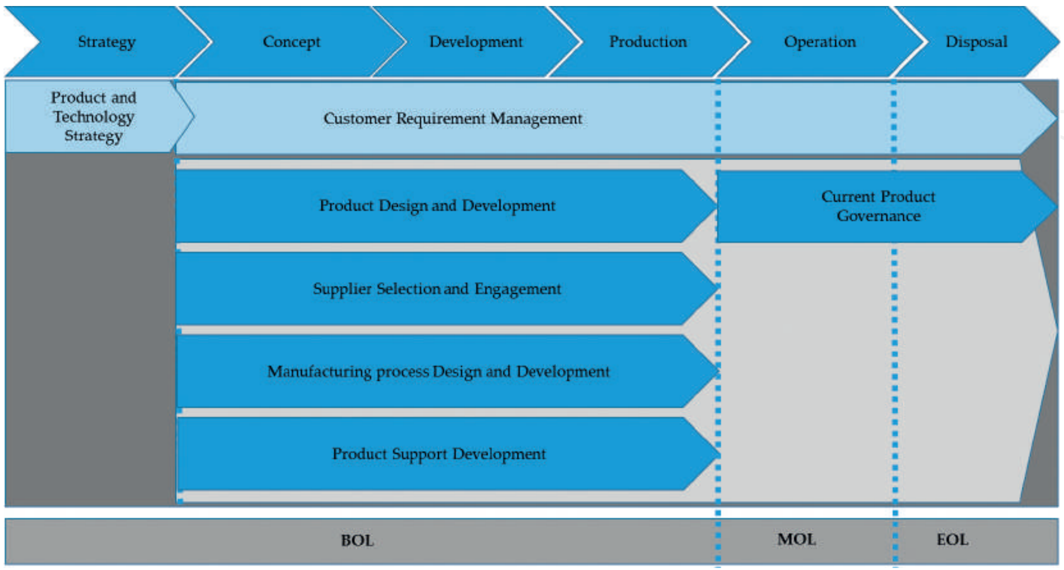


Figure 5. Product lifecycle management process model.

development. Although, this chapter will only discuss the product design and development activities but it is important to highlight that development of the company's product support starts in parallel with product design and development. Further, to aid support, the product is monitored by the company during its operation and up to its disposal.

3.1. PLM process model

The company's product development process mainly comprises two wide-ranging processes; the New Technology Introduction (NTI) process and the New Product Introduction (NPI) process. The general research and development exercise occurs through New Technology Induction (NTI) process in their research and Development (R&D) department before the NPI process starts. Emission-related legislation is a key driver in technology development for this company. New technology, for instance, an after-treatment system that will reduce engine emission, would be developed in the NTI stage, and this system would be integrated with the engine through NPI process. This chapter focuses on the NPI process as most directly aligned with generic product development and PLM. However, it is noted that the background processes of NTI critical in product lifecycle especially as new technologies come on stream during life, enabling redesign and retrofitting of new components and subsystems.

As shown in **Figure 6**, this NPI process in the company has seven stages starting from the identification of market needs to the review of a product's performance in the field, i.e. "Requirements" to the "Review of Market Performance" (see Tahera [4] for further details of the company processes). Each stage leads to a formal gate review. Based on prescribed criteria, a product must pass through review at the gateways (GW1, GW2,…GW7) before the product development project proceeds to the next stage.

Testing and the key activities of design, computer aided design and engineering (CAE), and procurement of prototypes are considered in this study. The latter is a major activity since these need specialist design and manufacturing expertise, often involving new manufacturing processes, materials and technologies. A more detailed flow diagram of these stages is presented in **Figure 6** to show the integration of the key activities.

As the diesel engine is a mature product and design changes happen incrementally, engineers in the company start with an existing analysis of the previous generation of products. For a new product introduction (NPI) programme, product objectives are checked against a current product issues (CPI) database. The CPI database provides information about failure modes and effects of current products, which will need special attention for next generation products. This process is carried out by lead team members who are the technical specialists, component owners, design owners and the verification and validation managers.

The NPI process starts in the requirement gathering phase, and should be finished before Gateway 1 (GW1), i.e. before the concept demonstration phase, however spread across the SD phase. Initially, the design alternatives are included in the analysis, because selection of a design is made based on the risk with that particular design and the associated time and cost of its validation program. All design options are considered during this phase. These help to analyse the trade-offs that can be made across different design options. If this analysis

http://dx.doi.org/10.5772/intechopen.80364

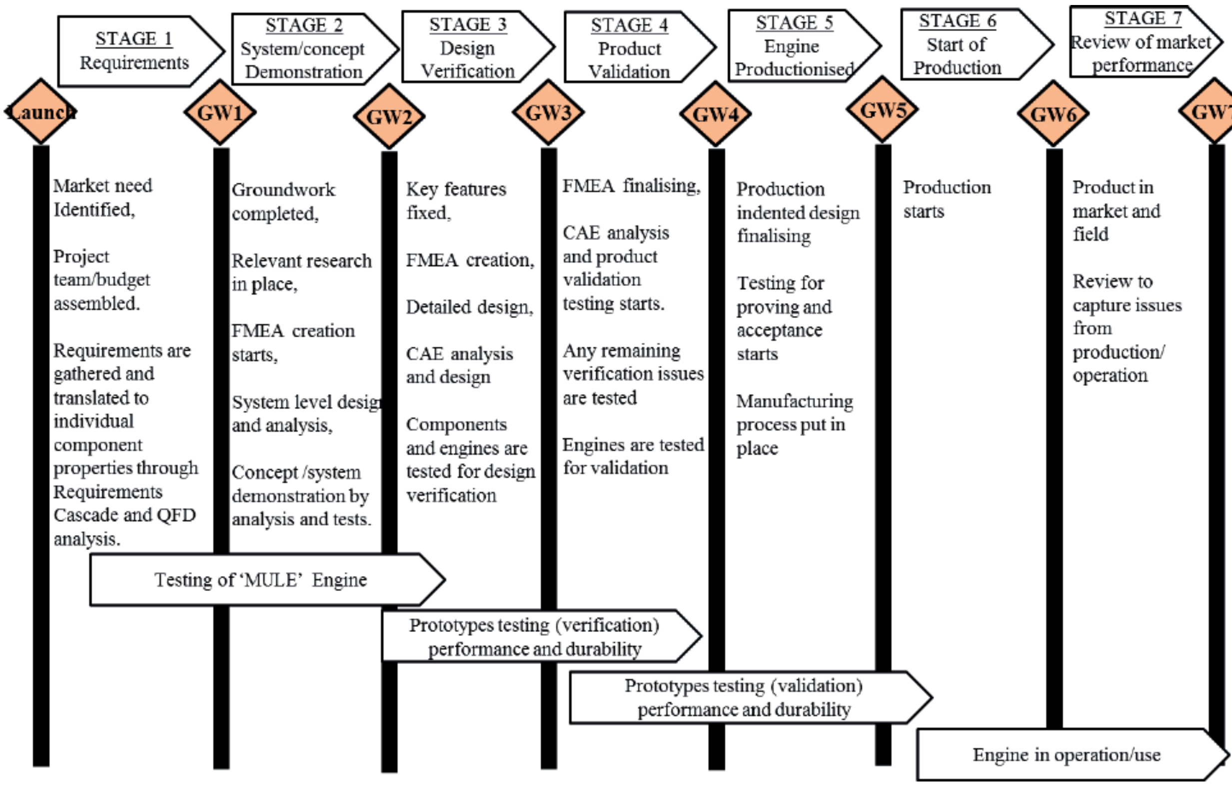


Figure 6. Stage-gate process for new product introduction in a company study.

identifies high risks in design decisions, CAE analysis and design changes are undertaken until the risk is reduced to an acceptable level to proceed with the project. These CAE analyses typically fall into three main areas: structural analysis, mechanism or dynamic analysis and thermo-fluid-flow dynamics. They result in the determination of parameters like material properties, geometric idealisation, and physics, which help to define the scope of the design activity. When the overall risks are assessed, design verification and validation actions are decided and planned to mitigate risk. Verification and validation activities can range from design changes, further CAE analysis to testing.

Ideally, most of the development related testing should start after the requirements have been identified i.e. after the Gateway 1 (GW1) and continue till the product is validated, i.e. until Gateway 5 (GW5), after which the engine is released to production. However, as depicted in **Figure 6**, these testing activities can spread further across subsequent stages of the process. At each stage, functional tests include the performance and emission (P&E) tests and mechanical tests for durability and reliability. Performance testing measures engines properties. For example, power and fuel consumption of an engine may be measured given a regulated fuel and air intake into the engine cylinder under steady state conditions of constant speed and load. While ensuring the performance, engines need to satisfy legislative conditions, for instance, the chemical constitution of the exhaust gases. The durability and reliability tests are conducted in peak harshness and tougher condition for a reasonably short period of time, called accelerated tests, forcing components or engine to fail/pass. For example, a gross thermal test procedure specifies the test cycle for determining the thermal fatigue resistance of core engine components. Typically, performance and emission related tests are performed before the mechanical durability and reliability testing.

Testing occurs at different levels of the product. Component level testing happens primarily at suppliers of components, although the case study company also carries out testing to investigate areas of design concern. Engine level testing involves standalone engines on a test bed. Machine level testing involves engines mounted in a machine or vehicle to reproduce expected conditions of use. **Figure 7** indicates how engine level and machine level testing are mainly conducted in parallel in the three consecutive stages, for different purposes in the product development and PLM. The stages are characterised by the type of testing activity. Stage 2 has Concept/System Demonstration (SD), stage 3 has Design Verification (DV), stage 4 has Product Validation (PV) and stages 5 and 6 focus on Certification.

Concept/system demonstration (SD) testing is primarily to demonstrate 'performance capability'. It shows that the technology can deliver the required performance. Alternative concepts are analysed and evaluated at this phase. A combination of old and new parts are built into an engine called a MULE. This MULE engine is tested to verify the performance of new parts.

Design verification (DV) is primarily to develop optimal performance and validate hardware at the optimised performance. The aim is to ensure that design outputs meet the given requirements under different use conditions. At this stage, testing focuses on the verification of a chosen design, through detailed analysis and testing of stress, strength, heat transfer and thermodynamics etc. This stage validates the hardware prior to commitment to expensive production tooling.

Product validation (PV) checks the effect of production variability on performance and any remaining hardware variation. This phase performs hardware testing which is limited to late design changes and emissions conformance testing. In this phase, detailed testing for reliability and durability occurs and the intended product is validated. The mandatory tests required for compliance usually occur during PV phases.

Testing for certification happens in stages 5 and 6 before product is released to customers. Global emission regulations for diesel engine manufacturers provide requirements for the testing and evaluation of new components and new engine designs. It is an imperative for certification that the company follows the standard regulations during product development in terms of how a product needs to build and tested during validation for certification. For instance, to meet the in-use compliance, the company needs to demonstrate that the engine will meet specific levels of particulate emissions that will be detected and measured at the end of the useful life of the product.

The case study company considers that testing of their product continues into use. As one senior engineer in the company remarked "*in fact, real tests start when products are in use*". Their engines are equipped with a remote monitoring system that allows them to capture and collect field data. They have special user groups and they have established close relationship with consumers who help to collect more reliable data. The data consists of equipment

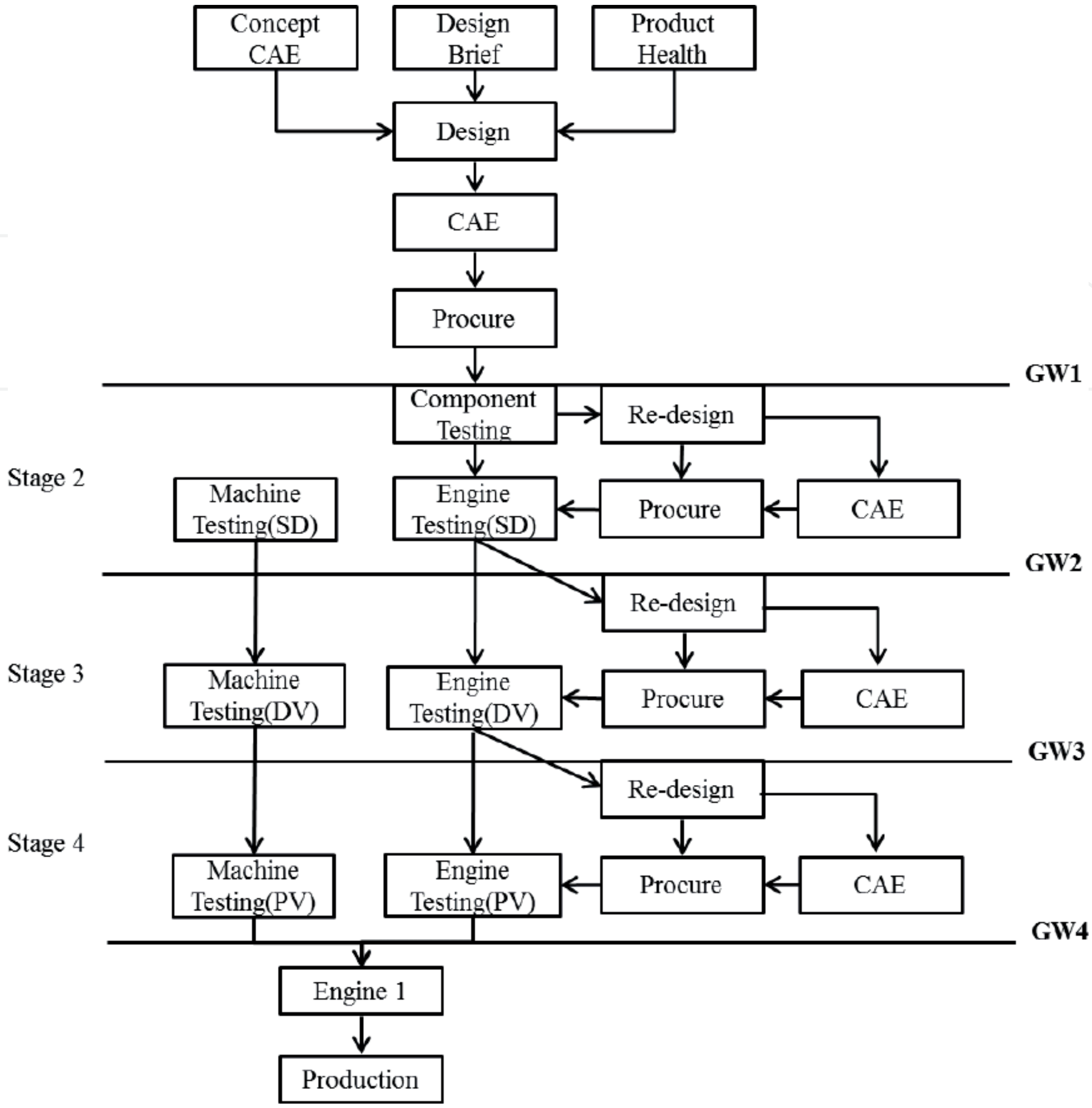


Figure 7. Flow diagram of testing and associated activities in diesel engine design and manufacture (adapted from [4]).

characteristics identification data, usually the unique numbers, operating data (engine on/off and physical variables), event data (failure and maintenance history) and environmental and condition data. These field data are useful for several reasons:

1. to monitor: how a product is used by a specific customer groups to identify any inappropriate and misuse,
2. to monitor the current health of the product to plan and design their aftermarket service, i.e. repairs and maintenance services.
3. to feedback to the beginning of the lifecycle as the product health monitoring data are the key input for designing the next generation of the product. This enables a reliable specification for the design phase and the development of a product description.

To help deliver these benefits the company creates two descriptions for monitoring and new product development in addition to the PLM descriptions mentioned in Section 2 for product, design and performance:

i. Current product governance—during product in operation/ field data to help new product development,

ii. Product support development—during product development to help product monitoring.

3.2. Current product governance: field data and new products

In the diesel engine company, the 'voice of the customer' (VOC) is captured in many ways: directly, through discussions, interviews and workshops with customers, and indirectly through analysing customer specifications, warranty data, and field reports etc. and through dealers and distributor channels. Quality Functional Deployment (QFD) is applied to identify critical technical requirements of the design which will need verification and validation by testing.

The company uses Failure Modes and Effects Analysis (FMEA) to evaluate a potential design for possible failures and to prevent them by proactively changing the design rather than reacting to adverse events after failures have occurred. This emphasis on prevention may reduce risk of failure in field. FMEA is particularly useful in evaluating a New Product Introduction programme prior to implementation as well as in assessing the impact of a proposed change to an existing design. More details about FMEA and steps of FMEA analysis can be found in [21]. FMEA is one of the most widespread methods used in determining priorities for technical risks in the PD process especially during the testing phase [22].

To identify the potential effects, the company reviews documents, including historical data, warranty documents, field service data, and customers' complaints. The company rates the severity of the effects of a failure mode. Any failure occurring in the field is considered as a high risk. Issues identified in use significantly drive next generation product development and testing procedures. The company continuously monitors and captures a product's performance and durability when engines are used in a field. For a new product development, the company uses information from the 'use in the field' to assess how the product is performing and from the 'use of the customer' (how customers are using the product) to judge when a potential failure is likely to occur.

Field data is particularly valuable as it consists of information about failures and repair actions that have been taken place under real operating conditions. This enables the acquisition of statistically significant reliability and repair data [23]. Issues in recording field incidents are addressed by Smith [23] particularly how reliance on people means that recording is subject to errors, omissions and misinterpretation.

3.3. Product support development: design for maintainability

Maintainability is characterised as the ease of retaining or restoring a product in effective use conditions by using specific procedures and resources [24]. It is an important factor in the economic success of an engineering system. "Design for maintainability requires an evaluation of the accessibility and reparability of the inherent systems and their related equipment in the event of failure, as well as of integrated systems shutdown during planned maintenance" [25]. Maintainability procedures and techniques not only avoid and fix failures they also consider how a system might fail. Three types of maintenance can be distinguished: breakdown maintenance (corrective maintenance), preventive maintenance, and predictive maintenance (condition-based maintenance).

Condition monitoring and fault diagnosis techniques are used for predictive maintenance [26]. Product health monitoring is a research area that covers failure detection, current health assessment and remaining useful life prediction [26, 27]. According to Fu et al. [28], most failures do not occur instantaneously. There is degradation and associated symptoms before the actual failure. The main objective of the predictive maintenance is to reliably identify these degradation processes so that maintenance can be affected before the actual breakdown. Predictive maintenance is based on the product's performance and condition monitoring data. For example, in well-established methods, vibration data is analysed to find the frequency responses to identify the type of fault present in the equipment [27].

At the design and development design stage the main characteristics of a product are determined and product performance is evaluated. Therefore, design for maintainability should be considered during the product development. However, according to Coulibaly et al. [29], there is lack of an efficient tool for considering maintainability and serviceability at the early design. Also, there is limited research on how information from design, CAE and tests can support product maintenance.

Kiritsis et al. [30] have commented that clear definition of the information for maintenance is required if appropriate and adequate information is to be collected. Usually, data collected during Middle of Life (MOL) phase of product is for maintenance management purposes and may not be appropriate for feeding back to the Beginning of Life (BOL) phase to redesign or improve a product. Although people involved in this process often have a clear understanding of the required information, it is not straightforward to define or determine exactly what information will be required.

A baseline performance description would allow degradation over a period of use to be assessed. As mentioned before, advanced engineering products such as the diesel engines studied here are equipped with instruments such as sensors, meters, controllers, and computational devices and have the processing capacity to self-detect/ predict certain problems. Next section proposes a conceptual model to facilitate this process. Design and testing data from the EOL stages can be a useful reference point for comparing with monitoring data for predictive maintenance. Also, this model can help to clearly define the information required to be collected to comparison.

4. Extending the proposition: testing data for predictive maintenance

This section extends a method for managing the iteration of design and testing during the product development stage [3] to predictive maintenance during the product use phase. First, the previous work will be described briefly, then how the work can be extended for the purpose of the predictive maintenance will be explained.

In an iterative design and testing process, testing results usually drive the subsequent re(design) activities. A control system analogy can be used to describe an iterative design and testing process. A control system monitors, compares and adjusts at a sequence of time points. A monitoring device makes a measurement, and reports it to the comparator, which compares it with the pre-determined desired value. A decision rule uses the result from the comparator to adjust an effector. Similarly, in a test, actual measurements of a parameter are taken and compared with pre-determined values identified in design analysis to identify if the design is satisfactory.

During a lengthy durability test, for example in a "Deterioration Factor" test, intermediary test measurements are taken at a sequence of time points between start t_s and finish t_f (t_s, t_1, $t_{2\ldots}$ $t_{n\ldots}$ t_f), as in **Figure 7**. Engineers know that the performance of an engine will change over the time and they allow an acceptable margin for each time point. This is illustrated in **Figure 8** with a range of expected values specified by design and CAE prior to the test. Engineers will know how much they expect the product to deteriorate after say 200 or 500 hours of running the test. If the product deteriorates below an allowable limit, or margin, at that time, then it is deemed under-designed. If an engine performs above the margin then it is assumed to be over-designed. Therefore, if the engine produces any value under or above the expected values (including margins) then these deviations are not acceptable (see **Figure 8**) and indicate that redesign is required. 'Deviation' is the difference between the expected value of a parameter and an actual measurement of that parameter, at the time of an assessment (e.g. test).

Figure 9 shows a schematic, which presents a simplified case of **Figure 8** in which the expected value is a single value rather than a range. In practice this might be the mean of the distribution of expected values and is represented as the upper straight line (in red). The lower line (in green) represents the measured values. A physical test starts at t_s and finishes at t_f. Since the design meets specification based on the best knowledge available at t_s, (or rather there is no information to indicate that it does not) the red and green line meet at t_s. During the testing process, test measurements are taken and the actual value of a parameter at any point is identified.

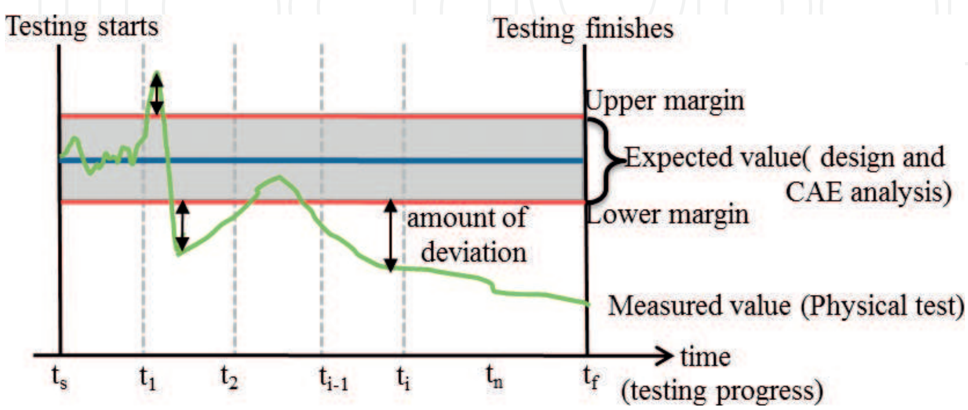


Figure 8. A schematic of expected and measured value and associated deviations at different times during a test.

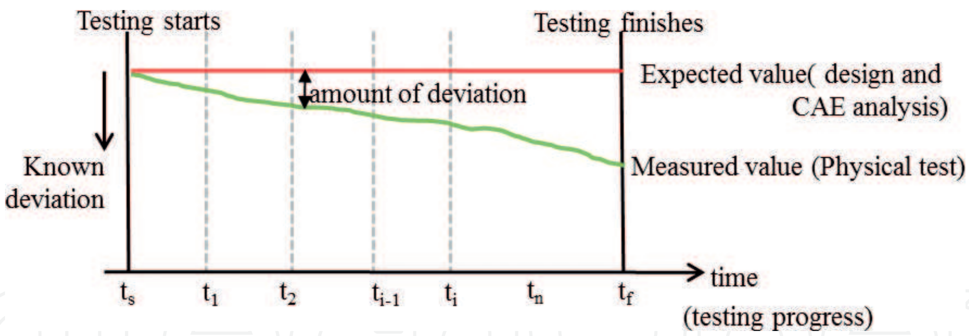


Figure 9. A simplified model of deviations between expected and measured values during a test.

Deviation, at a time point, is identified as the difference between test measurements and expected value. The magnitude of the deviation is shown with a double-headed arrow in **Figure 10** which depicts a case of under-design, with measured product performance gradually degrading and the deviation increasing monotonically. This considerable simplification is an assumption of the model developed here. The sloping line represents the evolution of test results over time, which tends to show increases in deviation of the design from expected performance. The deviation does not, in practice, decline linearly.

The difference between test measurements at different times, can reveal the 'degree of evolution' [12], i.e. how fast the deviation is changing in approach to the final value of the deviation at t_f. Details can be found in [12].

A similar proposition can be used for predictive maintenance. The design stage identifies the expected product performance in use, i.e. a range of expected values of a parameter can be specified by design, CAE and tests during the development stages. Product's health measurements are taken at a sequence of time points between start t_s and finish t_f (t_s, t_1, t_2 …..t_n….t_f), as in **Figure 9**. Using a similar approach as explained above, the "amount of deviation" and the 'degree of evolution' can identified.

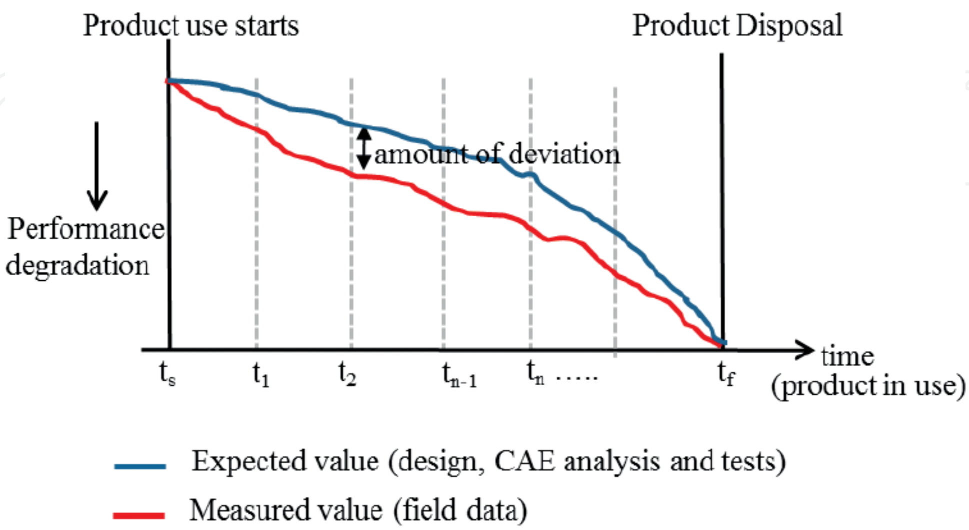


Figure 10. Comparison of CAE and test data with field data to identify product's performance level.

Once, these two factors are identified, i.e. how fast and how much within a time interval a product is degrading can be determined, an effective maintenance plan can be made.

5. Implications of the proposed method in PLM

The extension to include user and service data, combined with CAE simulations and test data to the latter stages of the product lifecycle in maintenance schedules and the refit of critical components is straightforward. As noted above the user and service data of previous products is used extensively in initial new product development, especially in FMEA and QFD processes. With a product currently in service, a history of user data will be accumulating. This serves several purposes. First to help specify and tune the maintenance schedules. Statistically significant data will be available from a large population of products about the behaviour, performance profiles and probabilities of failure of critical components in the product. This data is at the core of establishing service schedules and swop outs for potentially failing components.

Second, failing components can be identified for redesign and refitting. The use conditions and the causes of failure may be clear from the data. The cycle of product development will be repeated with simulation, physical test, often necessary for regulation conformance, and redesign. The methods of Section 4 which allowed convergence of simulation and virtual test results with those of emerging physical tests will enable a quicker time to redesign and replacement of the failing component with corresponding significant improvements in product performance and customer satisfaction.

Third, the emergence of new technologies at high technology readiness levels means that designs which were not feasible originally, because of the risks associated with low TRL can now be incorporated into the product. The purpose is to reduce costs, both to manufacturer and to consumer of the product. This process is frequently complicated by the dependence of the product developer on the processes of a specialist supplier. The advantages of the new and now mature technologies can be assessed against the use and service data. This will determine the benefits to all parties of the new technology and thus the business and engineering pressures on timescales. With an intense pressure on speed of product improvement through new technologies, there is considerable advantage in being able to overlap test and simulation of the performance of new technology. It is noted that as these processes continue further use data is continually made available. Using targeted use data in the mix of virtual and physical testing can assist in tuning the overlap, indeed there is the opportunity to install prototype new technology components in the current product and monitor use. This may help the convergence of simulation, test and use data.

Fourth, and consequential on the third, are the benefits of retrofitting. With a new technology embedded in a redesigned component, the opportunity may arise for variants, tailored to a range of use conditions. Which variant to retrofit and the associated programme of retrofit integrated with new maintenance schedules will depend on (i) performance characteristics of the variants from test and simulation and (ii) the specialised use data to match variant to user. This integration of test and use data, can assist the optimal choice of variants.

Across these processes for maintenance, refit and retrofit, the aggregated benefits of combining physical test, simulation and use data can be considerable. This can result in reducing time to introduction of revised maintenance schedules, to designing and fitting new technologies, as well as reduced costs to manufacturers and users. When all taken together the benefits to product lifecycle accumulate and make the argument for PLM systems to provide consistent and up to date information flows in supporting these processes.

In extending the model of overlapping test and design, using convergence between data sources, to these processes in the product lifecycle several additional descriptions arise in the PLM product model. These are driven by the necessity to manage the revised processes of product lifecycle which arise from the new data and new information flows, particularly in use and service data.

New process models and new product models develop hand in hand. This section has considered how product development and support through life cycle combines test, simulation and use data. Some general issues affecting PLM product models include how to compare this field data with simulation and test, the potential effects on information flows in the process models and the application of field data from one phase of product to the development process for next generation products, where fundamental analysis of the configuration and architecture of a product is undertaken over and above retrofitting new components and new technologies to the existing products.

Comparing field data with physical test is not straight forward. Usually, the case study company uses the accelerated testing methods in which tests are conducted in peak harshness and tougher condition for a reasonably short period of time. Most of the accelerated testing is to verify that the product will perform reliably during the useful life, until it starts to wear out. Physical test results might not be readily useful for comparing with the field data as the use conditions could be different, load cycle and sensor loading location could be different, for instance, CAE analysis and virtual testing can play an important role in comparing these test and field data. CAE analysis can model and control these conditions and can focus on individual parameters. The information of CAE analysis can be disaggregated into cycles, for example. Parameters can be analysed individually if required to support decision making. Analysis of these three data, i.e. CAE analysis, physical test and field data could provide useful information for predictive maintenance, as to analysis why and how a product might fail. This may also help to record/capture field data in an appropriate manner to be used by the design engineers for the next generation of the product.

The potential implications for PLM systems of the integration of design, test and field data in making information available in preliminary form to be used by PLM for dependent activities. This effectively overlaps activities previously linearly sequenced and reduces times and costs for customers and suppliers. However, such integration comes with a significant overhead. Increased numbers of cycles of revisions to the PLM descriptions is entailed as some preliminary information although sufficient to start subsequent activities may not be enough to finish them especially when on-site assurance and regulatory conformation are necessary before customer use.

6. Discussion and further research

PLM systems assemble and manipulate product descriptions, maintaining a product model. These descriptions come from many sources in the product development process including design, simulation, test and field data. To some extent the timely availability of descriptions is dependent on the process model used to organise and manage tasks. This chapter has addressed this issue through examining how a change to process models through integrating activities has an impact on PLM descriptions.

The main argument of this chapter is delineating further the relationship between the product models of PLM and the process models for planning product development. Karniel and Reich [1] make the case that product models of PLM, updated throughout product development, have the potential to drive the planning of adaptable and dynamic processes for product development. Along with other research (e.g. [14]), they develop methods and algorithms to derive dynamic process models from the updating product models of PLM. This view gives, in a sense, a priority to the product models of PLM. The 'new paradigm' of Karniel and Reich [1] provides a critical role for PLM in planning dynamic processes. Updated product models in PLM are used to update process models. Although, in many industry contexts, available information in PLM and other information systems is necessary for the management and organisation of the dynamic processes of product development, which are by nature contingent and dependent, it is not sufficient. There are imperatives and opportunities in managing processes can drive the modes and forms of information available to PLM.

This chapter has examined one aspect of this mutual dependency between product and process models. Making changes to process models through increasing the integration of test, simulation and acquiring field data, changes the requirements for product models and associated PLM systems. This research adds to the understanding of ways that process models drive the types of PLM systems necessary to support them. It complements the extensive body of research on the how PLM systems can drive dynamic and adaptable process models for product development. Considerable further research is required both in theoretical methods and in industry cases to optimise the costly and time consuming processes of testing, simulation and field data collection as well as integrating them with PLM systems.

Author details

Khadija Tahera[1]* and Christopher Earl[2]

*Address all correspondence to: k.tahera@hud.ac.uk

1 Huddersfield University, UK

2 Open University, UK

References

[1] Karniel A, Reich Y. Managing the Dynamics of New Product Development Processes: A New Product Lifecycle Management Paradigm. Springer Science & Business Media; 2011, Jul 28

[2] Stark J. Product lifecycle management. In: Product Lifecycle Management. Vol. 2. Cham: Springer; 2016:1-35

[3] Tahera K, Earl C, Eckert C. A method for improving overlapping of testing and design. IEEE Transactions on Engineering Management. 2017;**64**(2):179-192

[4] Tahera K. The role of testing in engineering product development processes [PhD Engineering and Innovation]. Milton Keynes: The Open University; 2014

[5] Tahera K, Wynn DC, Earl C, et al. Research in Engineering Design. 2018. https://doi.org/10.1007/s00163-018-0295-6

[6] Wynn DC, Clarkson PJ. Process models in design and development. Research in Engineering Design. 2018;**29**(2):161-202

[7] Srinivasan V. An integration framework for product lifecycle management. Computer-Aided Design. 2011;**43**(5):464-478

[8] Takata S et al. Maintenance: Changing role in life cycle management. CIRP Annals-Manufacturing Technology. 2004;**53**(2):643-655

[9] Daily J, Peterson J. Predictive maintenance: How big data analysis can improve maintenance. In: Supply Chain Integration Challenges in Commercial Aerospace. Cham: Springer; 2017:267-278

[10] Shabi J, Reich Y, Diamant R. Planning the verification, validation, and testing process: A case study demonstrating a decision support model. Journal of Engineering Design. 2017;**28**(3):171-204

[11] Engel A. Verification, Validation, and Testing of Engineered Systems. John Wiley & Sons; 2010;**73**

[12] Krishnan V, Eppinger SD, Whitney DE. A model-based framework to overlap product development activities. Management Science. 1997;**43**(4):437-451

[13] Moullec M-L et al. Toward system architecture generation and performances assessment under uncertainty using Bayesian networks. Journal of Mechanical Design. 2013;**135**(4):041002

[14] Lévárdy V, Browning TR. An adaptive process model to support product development project management. IEEE Transactions on Engineering Management. 2009;**56**(4):600-620

[15] Bufardi A, Kiritsis D, Xirouchakis P. Generation of design knowledge from product life cycle data. In: Methods and Tools for Effective Knowledge Life-Cycle-Management. Berlin, Heidelberg: Springer; 2008:375-389

[16] Li J, Tao F, Cheng Y, Zhao L. Big data in product lifecycle management. The International Journal of Advanced Manufacturing Technology. 2015;**81**(1-4):667-684

[17] Jun H-B, Kiritsis D, Xirouchakis P. Research issues on closed-loop PLM. Computers in Industry. 2007;**58**(8-9):855-868

[18] Kimura F, Suzuki H. Representing background information for product description to support product development process. CIRP Annals-Manufacturing Technology. 1995;**44**(1):113-116

[19] Howard TJ, Culley SJ, Dekoninck E. Describing the creative design process by the integration of engineering design and cognitive psychology literature. Design Studies. 2008;**29**(2):160-180

[20] Van der Auweraer H, Anthonis J, De Bruyne S, Leuridan J. Virtual engineering at work: The challenges for designing mechatronic products. Engineering with Computers. 2013;**29**(3):389-408

[21] Stamatis DH. Failure Mode and Effect Analysis: FMEA from Theory to Execution. ASQ Quality Press; 2003

[22] Segismundo A, Augusto Cauchick Miguel P. Failure mode and effects analysis (FMEA) in the context of risk management in new product development: A case study in an automotive company. International Journal of Quality & Reliability Management. 2008;**25**(9): 899-912

[23] Smith DJ. Reliability, Maintainability and Risk: Practical Methods for Engineers. Butterworth-Heinemann; 2017

[24] Stapelberg RF. Availability and maintainability in engineering design. Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design. 2009:295-527

[25] Stapelberg RF. Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design. Springer Science & Business Media; 2009, Feb 17

[26] Lu B, Li Y, Wu X, Yang Z. A review of recent advances in wind turbine condition monitoring and fault diagnosis. In: Power Electronics and Machines in Wind Applications, 2009. PEMWA: IEEE; 2009:1-7

[27] Choudhary AK, Harding JA, Tiwari MK. Data mining in manufacturing: A review based on the kind of knowledge. Journal of Intelligent Manufacturing. 2008;**20**(5):501

[28] Fu C, Ye L, Liu Y, Yu R, Iung B, Cheng Y, Zeng Y. Predictive maintenance in intelligent-control-maintenance-management system for hydroelectric generating unit. IEEE transactions on energy conversion. 2004;**19**:179-186

[29] Coulibaly A, Houssin R, Mutel B. Maintainability and safety indicators at design stage for mechanical products. Computers in industry. 2008;**59**:438-449

[30] Kiritsis D, Bufardi A, Xirouchakis P. Research issues on product lifecycle management and information tracking using smart embedded systems. Advanced Engineering Informatics. 2003;**17**:189-202

Chapter 6

PLM for Supply Chain Optimization

Imane Bouhaddou

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.81272

Abstract

Technological advances in science and technology information and communication in recent years have completely changed the way the enterprise functions. It works toward a collaborative relationship between the different partners of its supply chain. Thus, enterprises need to exploit the benefits of integrating supply chain actors and information sharing to improve their performances. This has led to the development of a collaborative product lifecycle management commonly known as PLM. The objective of this chapter is to propose a decision support tool based on PLM for supply chain optimization. Through this work, we conciliate two scientific communities: the one dedicated to PLM and the one relating to the problems relating to supply chain optimization.

Keywords: product lifecycle management (PLM), product design, supply chain design, optimization mathematical models, integrated logistics

1. Introduction

It is recognized that competition is shifting from "firm versus firm" perspective to "supply chain versus supply chain" perspective. Therefore, the ability to optimize the supply chain is becoming the critical issue for companies to win the competitive advantage [1].

Today, it is essential for firms to exploit the benefits associated with supply chain integration and information sharing to improve their supply chain performance [2, 3]. More efficiency can be achieved if this integration is done early in product life cycle particularly in product development process [4].

This has led to the development of systems to manage the technical data of the engineering process. It is in this context that the concept of product lifecycle management (PLM) was

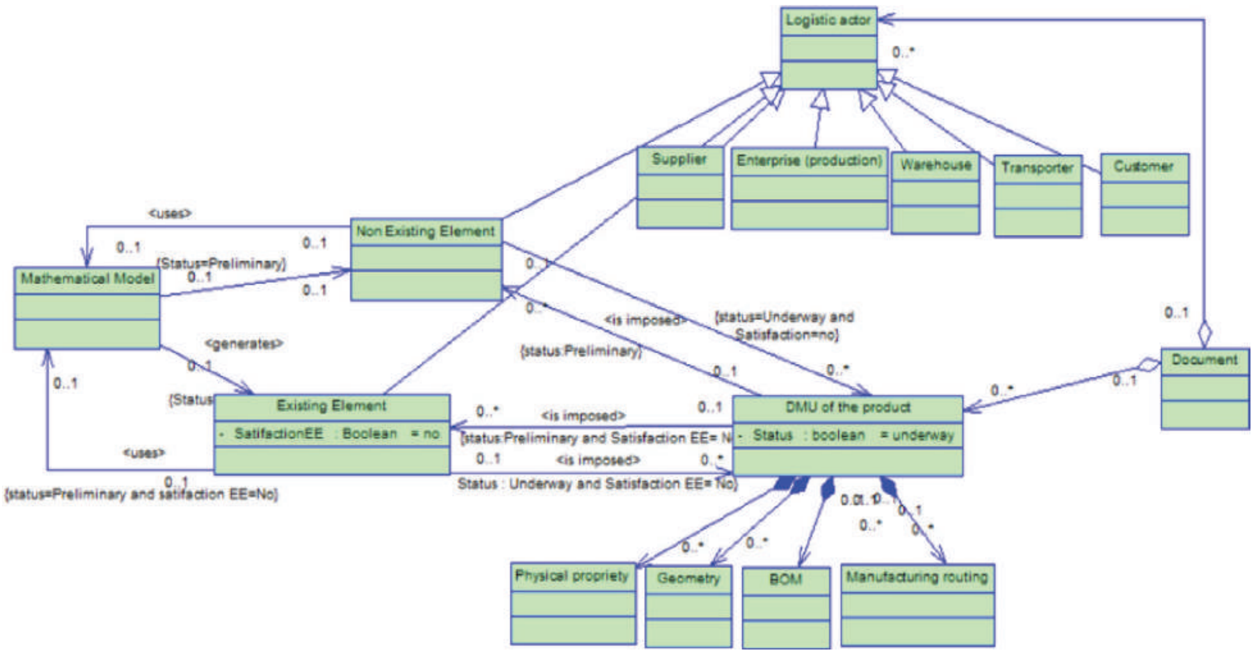


Figure 7. UML class diagram modeling the proposed methodology.

6. Conclusion

The competitiveness of a product on the market no longer depends on the company that assembles or sells it, but to all companies involved in the manufacturing process of this product and thus its entire supply chain. Therefore, the complex management of supply chains has increased the need for information exchange, sharing, and archiving.

Our work contributes to the field of integrated engineering, specifically the integrated logistics in the early stages of the product life cycle using PLM. Concretely, PLM enables a supply chain to become much more competitive by an effective collaboration among customers, developers, suppliers, and manufacturers at various lifecycle stages of a product.

In this chapter, we proposed a framework combining PLM and mathematical models to design the product and its related supply chain.

In our work, we defend the idea that the structure of the supply chain must be defined at the level of the product design that is to say at the level of the digital mockup. We then proposed a methodology based on the PLM approach for product design and its optimized supply chain.

Our approach takes into consideration, as a first step, the supply chain elements that already exist; their constraints must be integrated into the digital mockup. In a second step, designing new links must satisfy the digital mockup and the existing logistics network.

This approach combining PLM and mathematical models is based on three aspects:

- Organizational through the integration of the constraints of all the supply chain partners, responsible for main stages of the product life cycle.

- Technological by bringing together all the actors around the digital mockup; it structures the supply chain design.
- Mathematical by optimizing the costs of the different supply chain partners.

In our future work, we will implement the proposed methodology in two types of industries with different specifications: the agro-food packaging industry and the automotive industry.

Author details

Imane Bouhaddou

Address all correspondence to: b_imane@yahoo.fr

National High School of Arts and Crafts, Meknes, Morocco

References

[1] Barratt M, Barratt R. Exploring internal and external supply chain linkages: Evidence from the field. Journal of Operations Management. 2011;**29**(5):514-528

[2] Zhu W, Gavirneni S, Kapuscinski R. Periodic flexibility, information sharing, and supply chain performance. IIE Transactions. 2010;**42**(3):173-187

[3] Kiritsis D, Bufardi A, Xirouchakis P. Research issues on product lifecycle management and information tracking using smart embedded systems. Advanced Engineering Informatics. 2003;**17**(3/4):189-202

[4] Tang D, Qian X. Product lifecycle management for automotive development focusing on supplier integration. Computer in Industry. 2008;**59**:288-295

[5] CIMdata: Product Lifecycle Management. Empowering the Future of Business; 2003

[6] Garetti M., Macchi M., and Van De Berg R. Digitally Supported Engineering of Industrial Systems in the Globally Scaled Manufacturing, IMS-NoE SIG White Paper, Milano; 2003

[7] Terzi S. Element of product lifecycle management: Definitions, open issues and reference models, Phd thesis, University of Nancy I; 2005

[8] Sudarsan R, Fenes SJ, Sriran RD, Wang F. A product modeling framework for product lifecycle management. Computer-Aided Design. 2005;**37**

[9] Vezzetti E, Moos S, Kretli S. A product lifecycle management methodology for supporting knowledge reuse in the consumer packaged goods domain. Computer-Aided Design. 2011;**43**:1902-1911

[10] Paviot T. Methodology for Resolving Interoperability Issues in the Product Lifecycle Management Domain [Thesis], Ecole Centrale de Paris (France); 2010

[11] Christopher M. The agile supply chain: Competing in volatile markets. Industrial Marketing Management. 2000;**29**(1):37-44

[12] Bouhaddou I. Towards supply chain optimization: Proposition of conceptual models based on product lifecycle management PLM [Thesis], Le Havre University (France) and Moulay Ismail University (Morocco); 2015

[13] Bouhaddou I, Benabdelhafid A, Ouzizi L, Benghabrit Y. PLM (Product lifecycle management) approach to design a product and its optimized supply chain. International Journal of Business Performance and Supply Chain Modelling. 2014;**6**(3/4):255-275

IntechOpen

Chapter 7

Recycling of Polymeric Composite Materials

Emilia Sabău

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.81281

Abstract

This chapter treats studies about the methods and technologies used to recycle the polymeric composite materials and develop new recipes using waste of polymer composite materials resulted from recycling. Composite materials obtained from recycling are presented, with a complete recovery of waste glass fibers. Also, the mechanical properties for new structures of polymeric composite materials, containing additional materials were presented. These were obtained from the recycling of composite waste. A morphology analysis of fracture area of composites samples was done. At present, the polymeric composite materials present a great scientific and technical interest, which justify both the development of research in this field, and the expansion of production of such materials. The author treats aspects regarding a current problem due to the large number of polymeric composite materials waste, and reduced of environmental impact. This field is representing one of the top viable research directions.

Keywords: waste, composite materials, glass fibers, polymer matrix, recycled materials

1. Introduction

In the last decades have revealed significant changes in the world in terms of the use of materials in various fields, mutations complained so special requirements of peak areas and increasingly diversified requirements related to the production of consumer goods and not least all environmental requirements.

Composite materials are considered engineering materials that can replace non-ferrous or ferrous materials. Polymer composite materials have a large applicability in a different industries such as electrical engineering, electronics, building and civil engineering, rail, road and marine, aerospace technique and aeronautical, etc. [1–8].

Composite materials consist of reinforcement material (glass fiber, carbon fiber, Kevlar, etc.) and a matrix (polyester resin, epoxy resin, and so on). Fiber glass is the most used reinforcing materials. They have many characteristics: high tensile strength, high chemical resistance, low cost. To obtain low price or to give high properties to a composite material we can include in a structure auxiliary materials, like: coupling agents, catalysts, pigments, accelerators and so on [9].

The storage of waste composite materials and the recovery of these, it's an important problem that we have nowadays. In **Figure 1**, it can be seen composite parts out of use and composite waste resulted from different production processes that occupy considerable spaces for storage. In time the accumulation of such materials can create serious problems to the manufacturing companies.

Because the interest to find solutions for recovering or recycling is very low, the accumulation in time of composite materials waste is very significant. We can obtain a material rich in glass fiber by grinding the composite materials waste. Thus, it's obtaining a very valuable

a.

b.

Figure 1. Composite materials waste stored.

reinforcement that can be embedded in other materials or can be used for obtaining reinforced composite materials. A solution for recycling such composite materials has been to grind these materials, **Figure 2** and create new composite products.

The recovery and recycling of polymeric composite materials has experienced an important concern in the last years. Researches dedicated to technologies for recycling composite materials were initiated and carried out by different authors, [10–13].

Mixtures of concrete with sand and fiberglass waste are known [14–16]. Waste composites can be used for concrete reinforcement or for a variety of construction materials. However, these materials from the known technical solutions point of view have higher density, lower mechanical properties, and the external factors like: UV radiation, moisture, sunlight, influence the degradation of these.

A chemical recycling of glass fiber reinforced epoxy resin has been proposed by Dang et al. [17]. PET reinforced with glass fiber was recycled by Giraldi et al. [18], while Bartl et al. [19] study the fibers recycling obtained from tires. Vilaseca et al. [20] treat in their research recycled Kraft fibers (recycled softwood fibers) that coming from old sacs, used as reinforcement for the preparation of polypropylene composites. Composite materials obtained from wood fibers were analyzed by Nemes et al. [21] and Augier et al. [22].

Hugo et al. [23] were investigated recycled polymers with a range of different fillers, and developed applications that use waste thermoplastic polymer.

In order to make the ornamental plates used in the field of construction, a number of manufacturing processes are known which use sand mixtures with different binders: plaster, whitewash or cement [24, 25]. The obtained material as a dry mix or mortar is poured and pressed into a mold. After reinforcement of the material, the plate is extracted from the mold, after which time is left for stabilization, and then it can be used.

Figure 2. Ground glass fiber.

For the same purpose, for the production of alternative materials it is known the manufacturing process of reinforced mortars used in construction [26, 27]. These mortars include besides sand, whitewash, cement, gypsum and various reinforcement materials, such as: hemp fiber, glass fiber, etc.

The disadvantages of these processes are the high time of plates obtaining and their reduced mechanical characteristics. Other disadvantages of the plates obtained by these processes are the high density of the material and the degradation in time under the influence of external factors: humidity, sun, UV radiation.

Reinforced materials and manufacturing procedures have a significant influence on the quality, productivity and competitiveness of composite structures. The interface between matrix-reinforced materials plays an essential part in the mechanical behavior and fabrication of composite materials.

2. Recycling of composite materials

The recycling of materials organic macromolecular surgery is more complicated than with traditional materials (glass, paper, metal), because there is an impressive variety of polymers, which in most cases are not compatible with each other, in the event of a global recycling [28–30].

For the recycling of polymeric materials there are several solutions:

- The separation of the constituents of mixtures in order to recycling of each individual component;
- The direct transformation of the mixture without prior sorting, in order to reduce the volume of waste.

From the view point of recycling, waste can be classified as:

- Manufacturing waste (10% of total waste) mainly formed of a single material. Because they are not contaminated (or less purified) with other materials, recycling is easier. Typically, these wastes are reintroduced into production lines.
- Waste easily separable. They consist of 1–2 or more polymers (mix macroscopic scale) otherwise contaminated materials (fillers). These materials are, at least theoretically separable.
- Microscopic mixtures or intimately connected (soldered, interpenetration). This is the case most difficult to treat because the separation of constituents is difficult or even impossible, requiring complicated operations. In this category fits very well with organic matrix composites. The most representative example is the waste from the automotive industry. In this case, the blend will find materials (resins) thermoplastic, polymer mix, fibers, fillers and multilayer composite materials.
- Materials of the recycling, currently applies in particular to the first two categories mentioned.

The recycling after separation of mixtures is a much more interesting because you have to drive theoretically product with performance very close to the base polymeric materials. In practice, the properties of recycled materials approaching initial properties of the base material, unless methods are very effective waste sorting and waste have undergone significant degradation during operation.

Sorting of waste is done according to the basic polymeric material. The sequence of operations mainly comprises the following steps:

Shredding. At this stage, the materials must be recovered shrinks size to be easily transported and handled.

Separation of metals is well-established methods, obviating the mixture all existing metal fragments (e.g. electromagnetic methods).

- Shredding and/or spraying. This stage is complementary to the first mentioned. At this stage takes place and the washing waste. Choppers additional step is required for further processing easier.
- Washing and drying is intended to remove all impurities. In general washing is done with water and detergent, but depending on the nature of impurities at this stage can put complex problems. Flushing is required followed by spin drying to remove water.
- Separation using air or hydro cyclones and disposal are conventional methods for separating materials based on the difference in density. The process stream is brought into contact with a stream of air (water) in a cyclone. With these separation methods do not obtain high degrees of purity. Moreover, this mineral phase (mineral fillers) often change the apparent density of the polymer, making it difficult to separate.

By materializing the proposed project creates prerequisites for achieving scientific and technological results, competitive at European level in order to increase the visibility of Romanian research, especially to subsequently transfer the results in socio-economic practice.

The resolving of proposed assignment will lead to the development of science-based knowledge of the manufacturing processes of parts of polymeric composite materials reinforced with biodegradable waste. The aim is to achieve a topic fundamental research, advanced to develop methods and technologies for recycling polymer composite materials and develop new recipes using biodegradable waste. It thus aims to improve the quality, productivity and competitiveness of industrial products. This is possible by using a multidisciplinary approach to research that brings together knowledge of chemistry, mathematics, physics, rheology and technological engineering.

3. Proposed new composite material and manufacturing method for ornamental synthetic plates

Both composite materials and waste composite materials resulting from production processes occupy important storage areas with an impact on the environment.

It shows the utilization of the glass fiber waste obtained by grinding the waste resulting from the manufacturing technological process of composite materials or removing them from their use and incorporating them in a product with applications in the field of industrial constructions, offering superior mechanical characteristics to the existing similar products.

3.1. The matrix

The mold, for obtaining the ornamental synthetic plates, is made of two separate modules, one of silicone rubber and one of fiber reinforced composite material. In **Figure 3** are presented the steps of mold forming.

Achieving the active part of the silicone rubber mold eliminates the need for additional separation planes, and the mold stiffness is ensured by reinforcing it with a fiber reinforced composite material. The use of matrix mold from the silicone elastomer eliminates additional separation planes reducing the cost of the mold.

The manufacturing process of the matrix, involves the following phases:

- arranging the stones, **Figure 3(a)**,
- filling the joints with gypsum,
- forming the outer frame,
- applying the demulation layer, PVA (Polyvinyl alcohol),
- preparation and application of the silicone rubber, **Figure 3(b)**,
- realizing the composite structural element for the silicone mold, fiber glass/polyester matrix, **Figure 3(c)**,
- demulation of the mold from fiber reinforced composite material, **Figure 3(d)**,
- demulation of the mold from silicone rubber, **Figure 3(e)**,
- trimming edges, **Figure 3(f)**.

3.2. The material

The process of ornamental synthetic plates manufacturing consists in a mixing, in a recipient, of calcium carbonate with the polyester matrix 5 minutes, casting these materials into a modular mold made from silicone and reinforced by a fiber-reinforced composite material and maintaining at room temperature for 20 minutes until the matrix gel point has been reached, mixing in another recipient for 10 minutes of waste glass fiber ground with a polyester matrix and 0–0.3 mm sand, and molding it in the die over the initial molded material, holding molds in the die approx. 2 hours at 60°C, resulting an ornamental plate that is released from the mold after composite material polymerization. The material together with the unpolymerised matrix is deposited in a modular mold.

The sand was used as a low-cost reinforcement material in the form of particles with transparent aspect. The morphological analysis of the sand is shown in **Figure 4**.

http://dx.doi.org/10.5772/intechopen.81281

Figure 3. Steps of mold forming.

The manufacturing process of synthetic decorative plates involves the following phases:

a. preparing the mold and applying the first layer release agent,

b. preparing the first mixture consisting of 60% polyester matrix and 40% Calcium Carbonate $CaCO_3$, mixed approx. 5 minutes in a recipient,

c. casting the first mixture so that it will cover more than 1–3 mm the height of the mold asperities and the maintenance until reaching the gel point, at room temperature,

d. preparing the consolidation mixture consisting of 30% sand of the 0–0.3 mm sort range, 30% grinded glass fiber waste and 40% polyester matrix and mixing it for 20 minutes,

e. casting the consolidation mixture over the first mixture until the mold filling and leveling the upper part,

f. transferring the mold with the composite mixture in a polymerization heat and maintaining in the mold at a temperature of 60°C, about 2 hours, until the composite material polymerization,

g. mold release and obtaining the ornamental synthetic plates.

The composite material consists in obtaining a synthetic material composed of two component mixtures, **Figure 5**:

- the first mixture, which forms the surface layer that copy the mold and render the appearance of the synthetic plate, **Figure 6**, consist of 60% polyester matrix and 40% Calcium Carbonate $CaCO_3$, mixed approx. 5 minutes, casted and maintained until the gel point was reached;
- the second mixture, of consolidation, consist of 40% polyester matrix, 30% sand of the 0–0.3 mm sort range, 30% grinded glass fiber waste, casted over the first mixture and maintaining in the mold until the polymerization, resulting a synthetic composite material reinforced with glass fiber having superior mechanical properties to similar materials used in construction.

The percentages mentioned above represent the percentage of the total volume of the constituent materials.

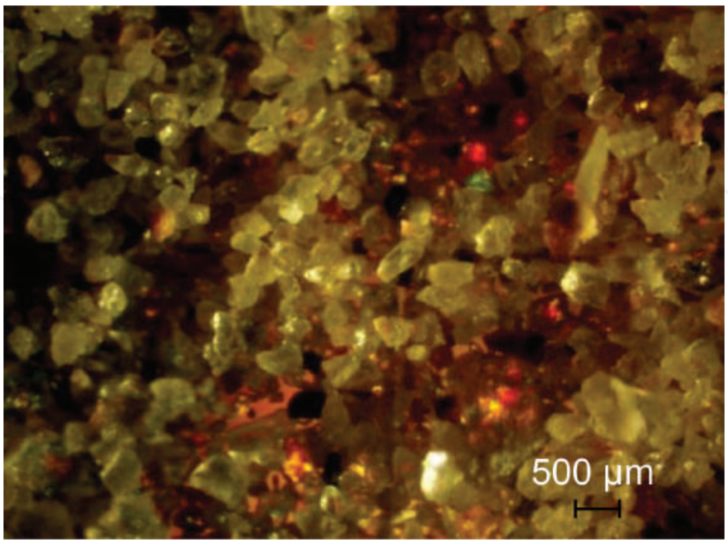


Figure 4. Sand grains.

Figure 5. The synthetic material consisting of two component mixtures.

The obtained material is a compact material with resistance at external agents, the process being easy to achieve. The composite material provides superior mechanical characteristics to traditional materials and can be used in other applications in the construction field such as reinforcing structures.

The following advantages are obtained:

- composite material waste utilization, thus solving the significant problem of glass fiber waste;
- enlarge the range of materials used in construction;
- making a composite material having superior mechanical characteristics and low density with respect to traditional materials;

- getting some plates with good look, imitating the natural stone, which can be colored in large quantity in the production process and can be easily mounted on facades and buildings;
- the technological simplicity of the process does not require substantial investment;
- the use of matrix mold from the silicone elastomer eliminates additional separation planes reducing the cost of the mold;
- increasing the mechanical characteristics when using these materials at low temperatures.

3.3. Mechanical tests

For mechanical tests, from the obtained material was done cubic specimens with 50 × 50 × 50 mm dimensions, according to EN 12320-3 standard.

The obtaining process of the composite plates that include in the structure glass fiber waste was hand lay-up. The mechanical properties of composite plates were determined to perform the experimental test at compressive load.

Figure 6. The ornamental synthetic plate.

http://dx.doi.org/10.5772/intechopen.81281

No.	Force [KN]	Average force [KN]	Average compressive breaking strength [MPa]	Density [Kg/m³]
1.	185.8			
2.	191.2			
3.	193.2	189.96	78.27	1380
4.	187.3			
5.	192.3			

Table 1. Compressive tests results.

Table 1 shows data following the compressive stress of cubic specimens, the constituent composite material remains bonded through filaments of reinforcement material.

The composite plates provide higher mechanical properties, lower costs and reduce waste materials in the environment.

The experimental data shows that the new materials have good mechanical properties and they can be successfully used in the dimensioning and verification process of composite structures resistance.

3.4. Microscopy study

The microstructure of fracture samples from waste glass fibers/sand/polyester matrix composites was analyzed using a metallographic microscope type Optika XDS-3 MET [31, 32].

The sand grains contain in the structure over 90% silica (SiO_2). The glass fibers are made from silica sand, which melts at 1720°C.

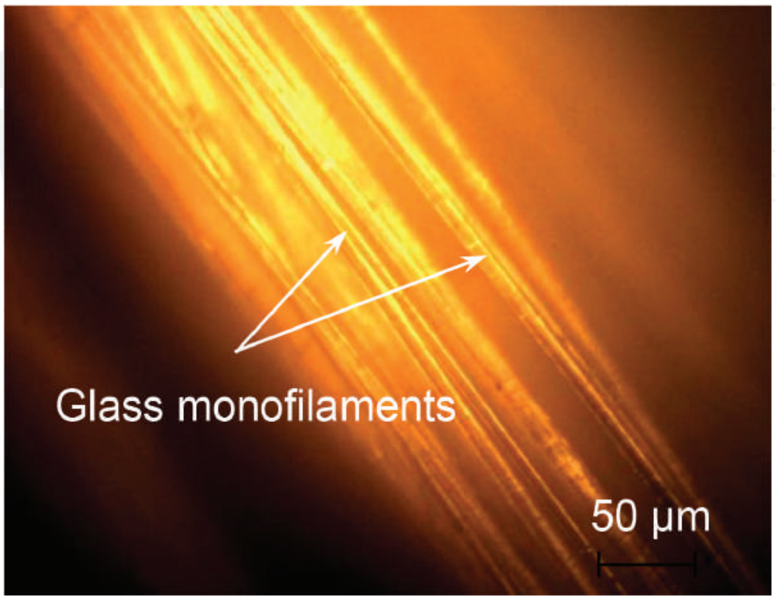


Figure 7. Non-impregnated glass fiber monofilaments.

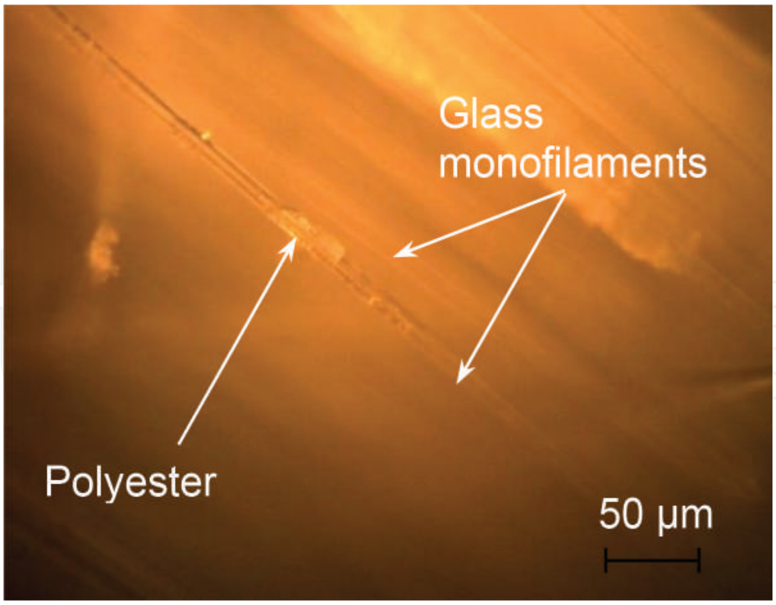
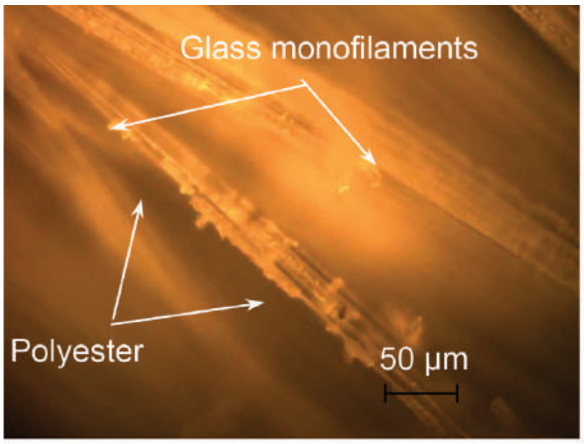
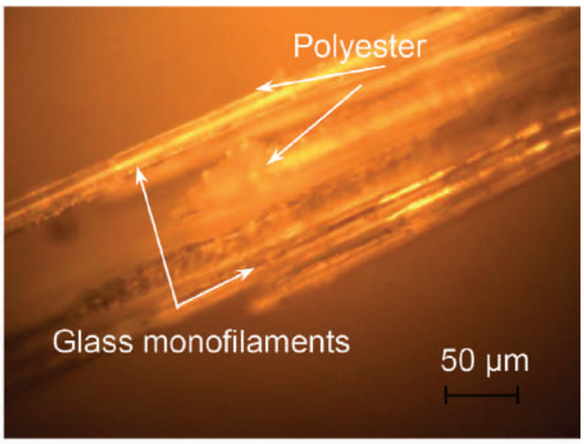


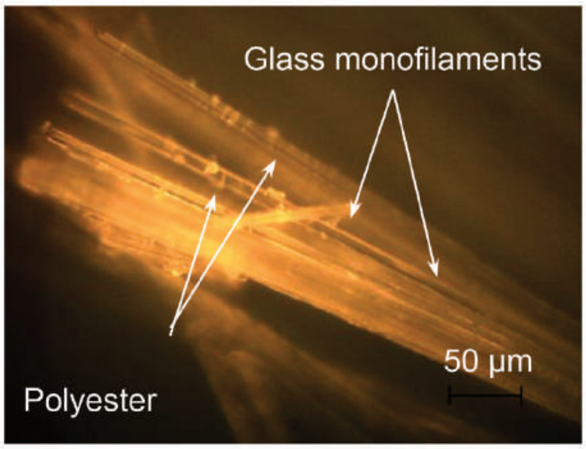
Figure 8. Impregnated glass fiber monofilaments with resin.



(a)



(b)



(c)

Figure 9. Waste glass fiber monofilaments impregnated with resin.

http://dx.doi.org/10.5772/intechopen.81281

The monofilaments of non-impregnated glass fiber have a smooth and glossy surface, specific to the glass. These were analyzed using the optical microscopy, **Figure 7**. To have a good adhesion at the interface between matrix and fibers, the surface of glass fibers is treated with silane. In **Figure 8** it's show the impregnated glass fiber monofilaments with resin.

Figure 9 shows the adhesion between matrix and glass fiber monofilaments. **Figure 10** illustrates that sand grains and glass fiber monofilaments are well impregnated with resin according to the morphological analysis of the fracture area. It can be observed a good compatibility between resin, filaments and sand, and a good impregnation of the matrix.

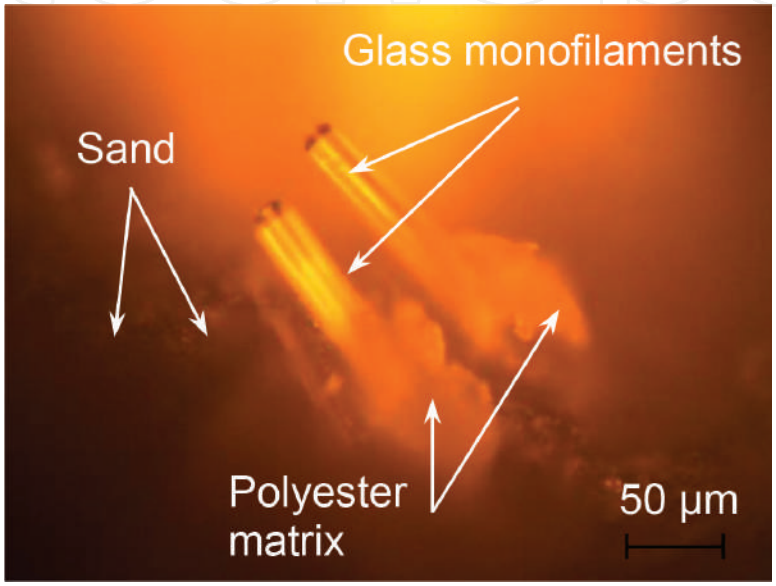


Figure 10. The fracture zone of waste fiber glass/sand/polyester resin plate.

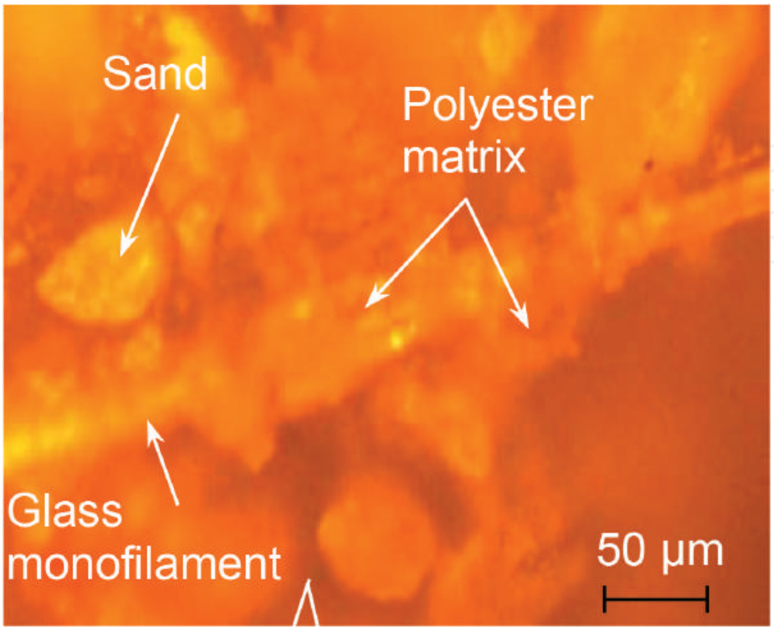


Figure 11. Sand and glass monofilaments in polyester resin.

According to the **Figure 11**, it can be observe the achieved connection between polyester matrix, glass fibers and sand, because of the particles of sand and polyester resin that were well glued on the glass monofilaments. Thus, a composite material with low density and high mechanical properties has obtained. These types of materials allow one reuse of glass fiber waste. Using these types of materials at low temperatures increases their mechanical characteristics.

4. Energy dispersive x-ray analysis

With the help of the energy dispersive x-ray spectroscopy (EDX) was performed the elemental analysis of the polyester resin and waste fiber glass. The weight fraction ratio is composed on the total weight of the chemical substances analyzed. The predominance of silicon and aluminum can be observed in the **Figure 12**, after the elemental EDX analysis was done of the waste glass fiber [32]. Also, small amounts of carbon, oxygen, sodium, magnesium and calcium are detected. The obtained data are expressed in two ways, both atomic percent (At.%) and weight percent (Wt.%). The atomic and the weight percentages of the fiber glass elements are: C with 30.96At.%, 17.67Wt.%; O with 24.12At.%, 18.34Wt.%; Na with 0.34At.%, 0.37Wt.%; Mg with 0.38At.%, 0.43Wt.%; Al with 14.43At.%, 18.50Wt.%; Si with 21.12At.%, 28.19Wt% and

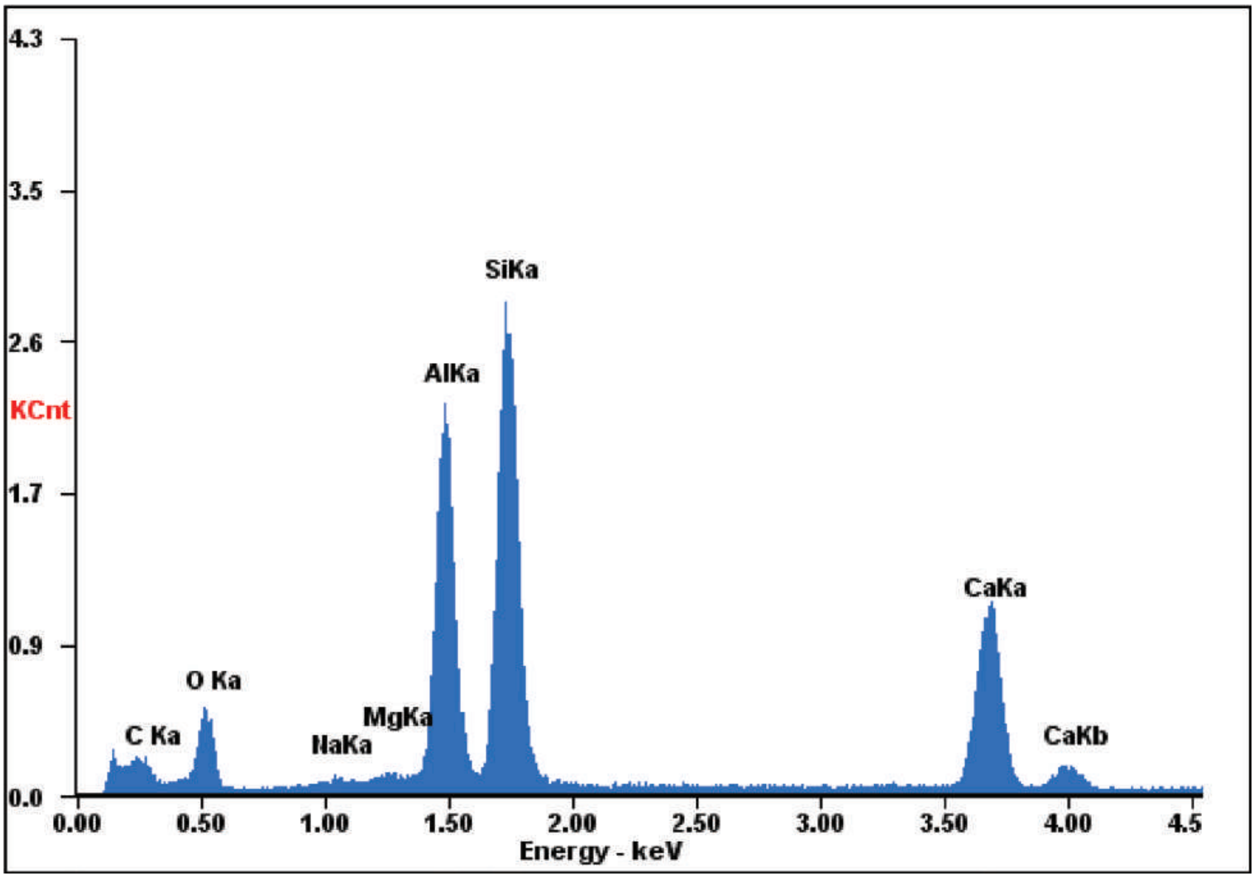


Figure 12. EDX analysis of the chemical constituents from the glass fiber.

Element	At.%	Wt.%
Si	21.12	28.19
Al	14.43	18.50
Ca	08.66	16.50
O	24.12	18.34
C	30.96	17.67
Mg	00.38	00.43
Na	00.34	00.37

Table 2. EDX analysis of the glass fiber.

Ca with 8.66At.%, 16.50Wt.%. In **Table 2** are presented the elements on the surface of a waste glass fiber.

The EDX analysis of the matrix polymer is presented in **Figure 13**, [32]. The predominance of carbon, silicon and oxygen is obviously in this case study. Also, small amount of sodium, aluminum and calcium are detected. The atomic and the weight percentages of the polyester matrix

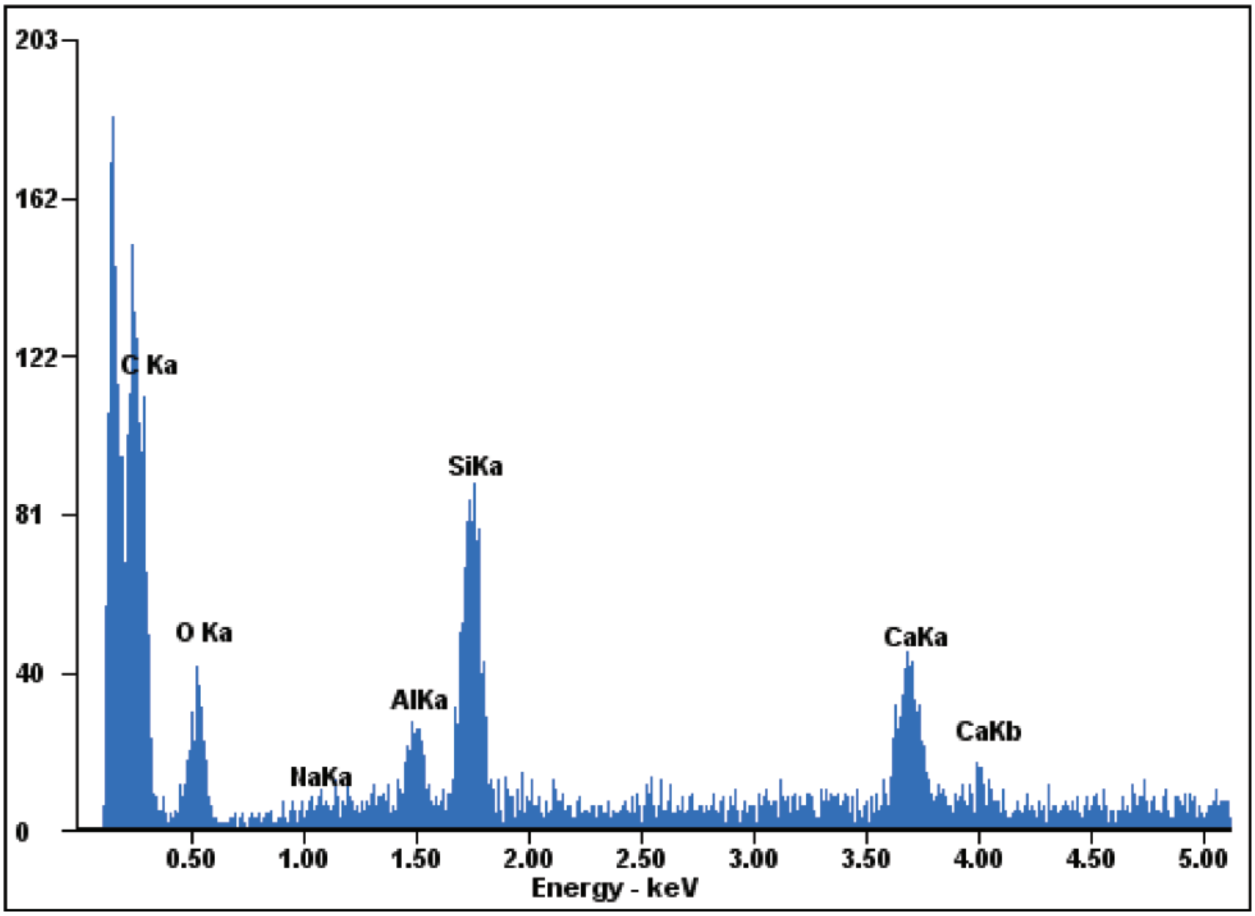


Figure 13. EDX analysis of the matrix polymer.

Element	At.%	Wt.%
C	74.80	62.18
Si	04.78	9.30
O	15.97	17.69
Ca	02.87	7.98
Al	01.28	2.39
Na	00.29	0.47

Table 3. EDX analysis of the matrix.

elements are: C with 74.80At.%, 62.18Wt.%; O with 15.97At.%, 17.69Wt.%; Na with 0.29At.%, 0.47Wt.%; Al with 1.28At.%, 2.39Wt.%; Si with 4.78At.%, 9.30Wt.% and Ca with 2.87At.%, 7.98Wt.%.

In the table above, **Table 3**, are presented the elemental quantitative analyses that give us the polyester matrix elements on the surface.

5. Conclusions

The storage of waste composite materials and the recovery of these, it's an important problem that we have nowadays. Composite parts out of use and composite waste resulted from different production processes occupy considerable spaces for storage. The manufacturing companies can be affected by serious problems, because of the accumulation in time of these types of materials.

A solution for recycling these composite materials has been to grind these materials and create new composite products.

A new composite material obtained from recovered materials, with a complete recovery of glass fibers waste is described in this study.

The composite material for obtaining the ornamental synthetic plates consist of a mixture that forms the surface layer, that copy the mold and render the appearance of the synthetic plate, consist of 60% polyester matrix and 40% Calcium Carbonate $CaCO_3$ and a consolidation mixture consist of 40% polyester matrix, 30% sand of the 0–0.3 mm sort range, 30% grinded glass fiber waste, casted over the first mixture and maintaining in the mold until the polymerization.

The experimental properties obtained indicate a very good mechanical behavior of the new composite materials. The compressive tests indicate a high value, superior of traditional materials, like concrete.

The fracture area of the samples from glass fibers waste/polyester resin/sand composites was microscopically analyzed. A good compatibility between resin, filaments and sand, and a good impregnation of the matrix was obtained.

The new composite material contained grinded glass fiber waste, polyester matrix and sand all mixed together. After polymerization of the resin we obtain a composite material with superior mechanical properties. This material can be used in different applications, like: strengthening composite parts (ornamental garden stones, ornamental composites plates, garden furniture, additive materials and so on), polyester reinforced concrete.

Acknowledgements

This paper was supported by the project AMATUC HORIZONT 2020, contract nr. GA 691787, "Boosting the scientific excellence and innovation capacity in Additive Manufacturing of the TUC-N (AMaTUC)", 2016-2018, project director: Nicolae Balc.

Author details

Emilia Sabău

Address all correspondence to: emilia.sabau@tcm.utcluj.ro

Technical University of Cluj-Napoca, Romania

References

[1] Barbero EJ. Introduction to Composite Materials Design. USA: West Virginia University; 1998. 336 p. ISBN 97e8-1-4200-7915-9

[2] Gay D. Matériaux Composites. 4th ed. Paris: Hezrmes; 1997. 640 p. ISBN2-86601-586-X

[3] Berthelot JM. Matériaux Composites. Comportement mécanique et analyse des structures. Paris: Editions TEC&DOC; 1999. 620 p. ISBN 2-7430-0349-9

[4] Ch D. Structures composites. Calcul des plaques et des poutres multicouches. Paris: Hermes; 2000. 352 p. ISBN 2-7462-0114-3

[5] Jones RM. Mechanics of Composite Materials. 2nd ed. Philadelphia: Taylor and Francis; 1999. 519 p. ISBN 1-56032-712-X

[6] Kollar LP, Springer GS. Mechanics of Composite Structures. Cambridge: Cambridge University Press; 2003. 480 p. ISBN 978-0-511-05703-8

[7] Vasiliev VV, Morozov EV. Mechanics and Analysis of Composite Materials. London: Elsevier Science; 2001. 41e2 p. ISBN 0-08-042702-2

[8] Cobzaru P. Materiale compozite (Composite materials). Bucureşti: Didactică şi Pedagogică; 2004. ISBN 973-30-1445-1

[9] Nemeş O, Lachaud F, Piquet R, Soporan VF, Tătaru O. The waste rubber used to improve the properties of composite materials. Studia UBB Chemia;**2008, 53**(3):25-30. ISSN: 1224-7154. WOS:000263940900002

[10] Pickering SJ. Recycling technologies for thermoset composite materials-current status. Composites Part A Applied Science and Manufacturing. 2006;**37**:1206-1215. DOI: 10.1016/j.compositesa.2005.05.030

[11] Turner TA, Pickering SJ, Warrior NA. Development of recycled carbon fibre moulding compounds – Preparation of waste composites. Composites: Part B. 2011;**42**:517-525. DOI: 10.1016/j.compositesb.2010.11.010

[12] Bernasconi A, Rossin D, Armanni C. Analysis of the effect of mechanical recycling upon tensile strength of a short glass fibre reinforced polyamide 6,6. Journal of Engineering Fracture Mechanics. 2007;**74**(4):627-641. DOI: 10.1016/j.engfracmech.2006.10.002

[13] Pickering SJ, Kelly RM, Kennerley JR, Rudd CD, Fenwick NJ. A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. Composites Science and Technology. 2000;**60**(4):509-523. DOI: 10.1016/S0266-3538(99)00154-2

[14] Sebaibi N, Benzerzour M, Abriak NE, Binetruy C. Mechanical properties of concrete-reinforced fibre sand powders with crushed thermoset composites: The influence of fibre/matrix interaction. Construction and Building Materials. 2012;**29**:332-338. ISSN 0950-0618

[15] Park SB, Lee BC, Kim JH. Studies on mechanical properties of concrete containing waste glass aggregate. Cement and Concrete Research. 2004;**34**:2181-2189

[16] Tam VWY, Gao XF, Tam CM, Ng KM. Physio-chemical reactions in recycle aggregate concrete. Journal of Hazardous Materials. 2009;**163**:823-828. DOI: 10.1016/j.jhazmat.2008.07.031

[17] Dang WR, Kubouchi M, Sembokuya H, Tsuda K. Chemical recycling of glass fiber reinforced epoxy resin cured with amine using nitric acid. Polymer. 2005;**46**(6):1905-1912. DOI: 10.1016/j.polymer.2004.12.035

[18] Giraldi ALF de M, Bartoli JR, Velasco JI, Mei LHI. Glass fibre recycled poly(ethylene terephthalate) composites: Mechanical and thermal properties. Polymer Testing. 2005;**24**:507-512. DOI: 10.1016/j.polymertesting.2004.11.011

[19] Bartl A, Hackl A, Mihalyi B, Wistuba M, Marini I. Recycling of fibre materials. Institution of chemical engineers. Trans IChemE: Part B. Process Safety and Environmental Protection. 2005;**83**(B4):351-358. DOI: 10.1205/psep.04392

[20] Vilaseca F, Mendez JA, Lopez JP, Vallejos ME, Barbera L, Pelach MA, et al. Recovered and recycled Kraft fibers as reinforcement of PP composites. Chemical Engineering Journal. 2008;**138**:586-595. DOI: 10.1016/j.cej.2007.07.066

[21] Nemes O, Chiper AM, Rus AR, Soporan VF, Tataru O, Bere P. New composite materials plates from vegetal fibres. Studia UBB Chemia. 2010;**54**. Sp.Iss. SI. 101-108 p. ISSN: 1224-7154. WOS:000208359300011

[22] Augier L, Sperone G, Vaca-Garcia C, Borredon ME. Influence of the wood fibre filler on the internal recycling of poly(vinyl chloride)-based composites. Polymer Degradation and Stability. 2007;**92**:1169-1176. DOI: 10.1016/j.polymdegradstab. 2007.04.010

[23] Hugo AM, Scelsi L, Hodzic A, Jones FR, Dwyer-Joyce R. Development of recycled polymer composites for structural applications. Plastics, Rubber and Composites. 2011;**40**(6-7): 323-317. DOI: 10.1179/1743289810Y.0000000008

[24] La PR. Sculpture—Méthodes et matériaux nouveaux. Paris: Dessain et Tolra; 2001. 64 p. ISBN 2-04-720032-6

[25] Le PR. Moulage. Paris: Dessain et Tolra; 2001. 158 p. ISBN 2-04-021842-4

[26] Mohanu I, Georgescu M, Mohanu D, Manolache L, Draganoaia C. Physical-mechanical and aesthetic characteristics of some mortars based on lime-limestone-volcanic tuff. Romanian Journal of Materials. 2011;**41**(4):332-345. ISSN: 1583-3186. WOS:00029820 4200005

[27] Rapisca P. Materiale de construcții (Building Materials). Bucuresti: Matrixrom; 2006. 480 p. ISBN 973-755-067-6

[28] Thomas C, Lombillo I, Polanco JA, Villegas L, Setien J, Biezma MV. Polymeric and cementitious mortars for the reconstruction of natural stone structures exposed to marine environments. Composites Part B Engineering. 2010;**41**:663-672. DOI: 10.1016/j. compositesb.2010.08.007

[29] Popescu V, Horovitz O, Damian L. Compozite cu matrice organic (Organic Matrix Composites). Cluj-Napoca: UTPRES; 2001. 327 p. ISBN 973-9471-97-8

[30] Bere P. Materiale compozite polimerice (Polymeric composite materials). Cluj-Napoca: U.T.Press; 2012. 252 p. ISBN 978-973-662-723-1

[31] Sabău E, Bâlc N, Bere P. Mechanical behavior of new composite materials reinforced by waste glass fibre. Advanced Engineering Forum. Switzerland: Trans Tech Publications; 2013;(8-9):309-316. DOI: 10.4028/www.scientific.net/AEF.8-9.309

[32] Sabău E, Bâlc N, Bere P, Nemes O. New materials from waste glass fibre. Studia Universitatis Babes-Bolyai Seria Chemia. 2012;**LVII**(4):201-208. ISSN 1224-7154. WOS: 000318593300020

IntechOpen