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Interpreting process data of wet pressing process. Part 1: Theoretical approach

Jana Bergmann[1], Hans Dörmann[1] and Rüdiger Lange[2]

Abstract

The wet pressing process represents a new production method for carbon fibre-reinforced plastics components. Due to the low cycle times, it is suitable for use in the automotive industry. Therefore, a sufficient degree of industrialisation needs to be achieved, which is characterised by a stable process. The knowledge about relevant process parameters, their interactions, and influence on the part quality builds the basis of an economic process. This is a major challenge, since in the early stage of process development the available amount of recorded process data is small and the data sets are not complete. As the implementation of time-, material-, and cost-intensive experiments represents no acceptable alternative, a theoretical approach is chosen. This article describes a theoretical procedure to define the critical factors of the wet pressing process with significantly less resource input.

Keywords

Wet pressing, process monitoring, layered structures, nondestructive evaluation

Introduction

It is a major challenge to industrialise the production of carbon fibre-reinforced plastic (CFRP) parts for the automotive industry. Since especially reduced cycle times are significant, the wet pressing process is an efficient alternative to established processes like the Resin-Transfer-Moulding (RTM).

The manufacturing process can be divided in three steps. These are the resin application, the pressing of the parts and the cooling procedure (Figure 1).

First the resin application takes place outside the tool. The tempered resin components are combined in a mixing head and applied on the fibre material by a slot die. After a defined impregnation time, the semi-finished fibre part is transported automatically to the press and deposited into the opened, heated two-part tool. Tool temperatures above 120°C depending on the used resin system accelerate the cross-linking reaction. With the tool closure, the fibres and resin are pressed into the cavity. During this step the material is compacted, the resin flows to all areas of the cavity, and the remaining dry fibre material is completely impregnated. By applying a defined pressure, the required fibre volume fraction is achieved. After the curing time, the component is removed from the wet pressing tool and transported to a cooling press. Inside the cooling press, moderate temperatures around 60°C allow a slowly cooling of the part to avoid stresses in the material and enable a complete curing of the component.

Since wet pressing is recently used by automobile manufacturer to produce body parts in a series production particularly the implementation of this new technique is a major challenge in the early stage of the production process. The execution of trial series including the pressing of test components and laboratory experiments is necessary to identify and verify the influences of individual process parameters and material properties on the party quality. In addition to the considerable expenditure of time, there is a large amount of the expensive carbon fibre wasted for these trials.

Time and cost saving measures such as filling or draping simulations are due to the many processing steps and parameters extremely complex. Beginning with the draping behaviour of the different fibre semifinished the simulation model can be extended by the macro- and

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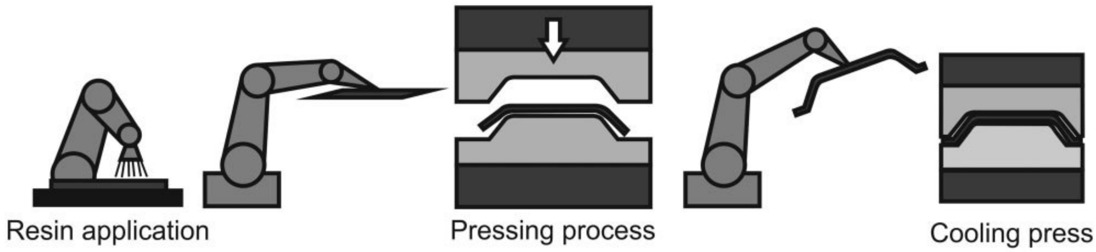

Figure 1. Production flow of wet pressing process.

micropermeability, the friction behaviour or fixing, e.g., by stitching points of the fibre materials.[1–3] Therefore, also the impregnation process that is influenced by the resin system can be integrated. This includes the material behaviour of the resin system, which is influenced by its reactivity and the applied temperatures as well as the resin application pattern and the capillary effects of the fibre material or race tracking between fibre semifinished and tool surface.[3–5]

The literature analysis showed that flow simulation approaches as well as compression simulations known from the RTM process are not available for the wet pressing process.[6–9] Also the draping simulation of dry fibre material may only partially be adapted, because the slipping behaviour of the single fibre layers varies by the influence of the uncured resin.[2,10] Since the resin application differs from the vacuum-assisted variants of Liquid Composite Moulding (LCM) also online control methods for a systematic process control cannot be adapted and other measuring techniques must be applied.[11,12]

In the early process phase, a representative data collection is hardly available. This has the consequence that applying numerical analyses on the process parameters and optimisation loops are difficult.[13]

Since for the wet pressing process no proper simulation methods are available, it must be resorted to theoretical approaches. They have, e.g., the potential to identify the right pretreatments for materials or to figure out customer relevant product properties.[14,15] This article presents a theoretical approach that initially covers the requirements of wet pressing components and the variety of process properties to identify critical factors and their interactions.

Preparation of theoretical approach

Various methods of the quality management are used for the implementation of the theoretical approach. The general procedure corresponds to the Quality Function Deployment (QFD) and ‘‘House of Quality’’ (HoQ) by Akao, which allows a structured analysis of the process and can be divided into several stages.[16] First the requirements must be defined, which are imposed on a body part made of CFRP. The next step is the identification of all factors. The 6M method by Ishikawa provides sufficient opportunities to identify all relevant parameters.[17] With this information, a matrix is created and rated by a team of experts to identify the required critical factors.

Defining requirements

The definition of the component requirements depends on the type of the part. For instance, the requirements for electronic components are significantly different to those of automotive body parts, which are considered in this article.

As in the automotive industry the passenger safety is always in the first place, the fulfilment of strength requirements is an essential criterion. Small defects on components such as dry spots can affect the mechanical properties of the part and have to be minimised. Since defects in fibre-reinforced plastics cannot be avoided completely and not every defect leads to a failure of the component, the term feature fits better. For the required low-stress assembly of the components, it is also necessary that the dimensional accuracy is guaranteed. Even a small component distortion can lead to installation difficulties or tensions within the components in the installed state. For the evaluation of the dimensional accuracy fixation points such as pure resin geometries can be integrated in the component, which have no function in the vehicle but serve for clamping the parts in measuring gauges or testing stations. Therefore, the fixation points have to be fully formed, which are also important for corrosion aspects. Since parts with defects in these areas can be leaky, the contact with water may cause corrosion. In addition to the listed requirements above, it is necessary that the component meets the vehicle specification. This includes the possibility that attachments can be installed as well as the component is durable and meets the requirements for the further process flow. The last point is the surface quality that plays a minor role for body parts since they are not in visible range. Uneven or heavily

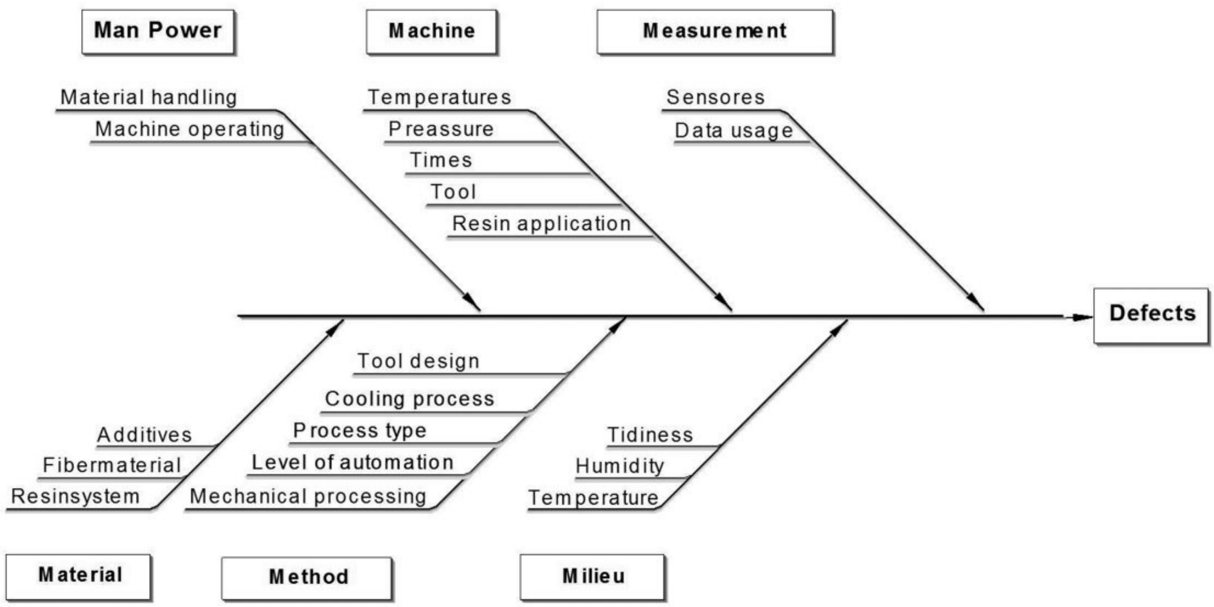

Figure 2. Standardised cause-and-effect-diagram for wet pressing process.

contaminated surfaces can affect bonding problems or exposed carbon fibres can cause corrosion of attachments.

Identifying parameters

For the identification of relevant process parameters, the 6M method of Ishikawa is a very good and simple method.[17] On this way, the factors can be collected in a structured way. A distinction is made between the following six areas: Machine, Method, Material, Man power, Measurement, and Milieu. Applied to the wet pressing process factors that affect the production process itself may be assigned to the Machine category, whereas the point Methods includes the way of the system implementation and its associated process steps. For the production of high-quality CFRP products, the quality of the raw material is of great importance and considered in the category Materials. As a manufacturing process cannot be completely automated, particularly in the early process phases, manual steps play a key role and are listed under the point Man power. Also relevant is the quality process and its control steps, which are attended in the Measure block. The last area of influence represents the environment of the production line – the Milieu. A collection of the most important influencing factors is shown in Figure 2.

It is important to note that this is only a rough overview for a standardised process. There can be defined a lot of subitems concerning each element of the 6M diagram. For the HoQ and the QFD, it is important to collect and include all subitems for the process-specific manufacturing conditions.

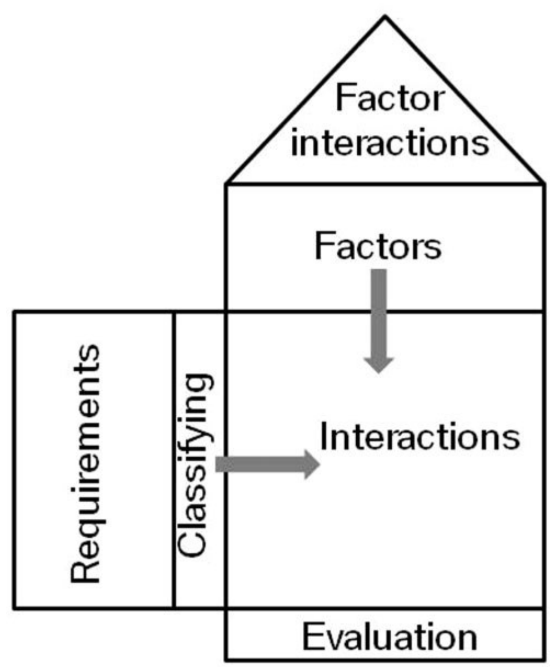

Figure 3. Structure of House of Quality.

In the production of fibre-reinforced plastics, there is an enormous variety of possible factors, including the manufacturing process and its parameters as well as environment conditions. Even the properties of the

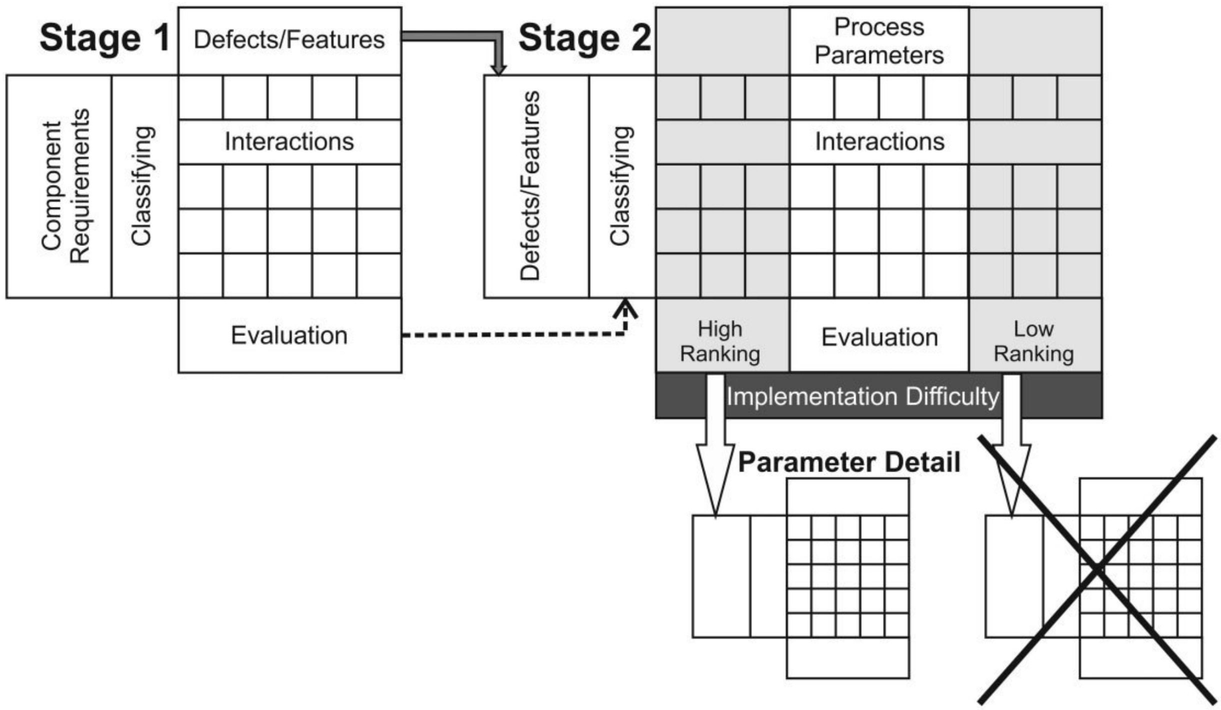

Figure 4. Stages of process evaluation.

raw material can have a great impact on the later part quality. Similarly it is difficult to define specific interactions between feature and parameter due to the large number of parameters. So in addition to the process factors, possible features such as dry spots, wrinkles in the semifinished fibre material and foamy resin areas were also listed in order to make a statement about possible interactions within this study.

Generating matrix

The base of the matrix, which is developed in the study, is the QFD or HoQ by Akao, which is modified according to the analysed process.[16] In addition to the evaluation of the requirements in dependence of the influence factors, which are getting evaluated, the HoQ as shown in Figure 3 considers the possibility to evaluate the interactions between the process parameters.

The QFD provides a stepwise analysis for extensive processes. In this study, two stages were chosen for the wet pressing process to identify interactions between part requirements and features simultaneously to those between features and process parameters. For this purpose, the component requirements, which were defined in the previous step, have been used in the requirements field of the first stage. Those are not directly compared to the process parameters. There is an intermediate stage with the previously collected features of components. So in the first step, the correlation between features and requirements is assessed. Then the most influential features are transformed to the requirements for the second stage. In the case of the component features, the purpose is avoiding and not creating them. At this point, the correlation between features and detailed properties of raw materials, process parameters, procedures, influence of manual processes and measurements as well as the environmental conditions, which were previously determined by the 6M method, is assessed Figure 4.

Since the contact between resin and fibre material occurs outside the press, the resin application and impregnation of the fibre material are considered in isolation of the pressing process. From this separate matrix, the most influential factors are linked to the second stage of the matrix for the pressing process. Isolated analyses would also be suitable for upstream processes such as production of the semifinished fibre material or subsequent processes such as the mechanical processing of the components. When the matrix is fully prepared, it has to be assessed in the last step. This procedure is described in the next section.

Evaluation of the theoretical approach

The evaluation is performed by a team of experts from different technology areas such as the manufacturing process, semifinished fibre products, resin system and

Table 1. Requirement evaluation.

Requirement	Classifying
Strength requirement	5
Dimensional accuracy	5
Fixation point accuracy	5
Vehicle specification	3
Surface quality	1

Table 2. Legend of parameter evaluation.

Evaluation	Symbols
0	○
1	◔
2	◑
3	◕
4	●

process planning concerning the wet pressing process. It starts with the classifying of the component requirements. There are three different classes. If the requirement is safety relevant or the part cannot be installed, the classifying is set to 5, if a deviation leads to a limited functionality, it is set to 3 and for the less important, which do not cause a critical malfunction, a value of 1 is chosen. For example, the following values have been determined (Table 1).

An appropriate scale needs to be defined for the assessment of the interactions among requirements and features. In this study, five different levels have been adopted to highlight the differences in the individual features clearly (Table 2).

For very strong correlations, the field is rated with 4. If there is a strong relation between the factors, the classification is 3 and for medium strong the value 2 is chosen. If there are only low interactions, 1 is selected and if no interaction, exists 0 can be used. Now the features and their influence on the component requirements are evaluated by columns until the matrix is completely filled. The analysis of the results follows subsequently. First, the absolute significances a_i of the influence factors are calculated. Therefore, the sum of the products of requirement classifying c_i and feature interactions f_i is formed

$$a_i = \sum_{i=1}^{n} c_i \times f_i \tag{1}$$

The number of summands n corresponds to the number of requirements. By accumulating the absolute significances c_i, the relative significances r_i can be calculated by dividing by the number of features m

$$r_i = \frac{a_i}{\sum_{i=1}^{m} a_i} \tag{2}$$

For this example, which is based on five requirements, the maximum absolute significance of a feature can be 76, if for all combinations very strong interactions are assumed. Accordingly can be said the higher the influence of the feature the higher the absolute and relative significance. This first stage enables the evaluation of the features to emerge the factors with the greatest impact on the quality of the fibre reinforces plastic components (Figure 5).

In the second stage, the dependence among feature formation and individual process parameters will be evaluated to identify the cause of their formation. This context also provides insights into the interactions among component requirements and production properties since these are taken into account by classifying the features. Therefore, the beginning of the second stage is the classifying of the features that are transformed into the requirements of the second stage. This is done based on the relative significance. Approximately 20% of the highest ratings receive the classifying 5. For the subsequent 40% of features, a rating of 3 is selected and the remaining 40% receive the lowest rating of 1. Especially in border areas of the subdivision should be checked for plausibility by the team of experts evaluating the matrix to get sure the right classifying is assigned. As in the first stage the next step is the assessment of the relationship among features and parameters as well as ancillary conditions by a team of experts. The calculation of the absolute and relative significance allows a clear exposure of the most critical factors (Figure 6).

In the overview can be seen that only one of the properties concerning the resin system got a low ranking. Since there is a high influence on the party quality and the process parameters are broadly defined in the second stage, a detail matrix is created for a deep analysis (Figure 7).

Requirements	Classifying \ Defects/Features	Cross folds / strong waviness / locks	Longitudinal folds	Laid open fibres / dry spots	Pores / foamy areas / defects	Air locks / air gaps	Residue / entrapments component	Residue / entrapments environment	Inhomogene material areas	Cracks	Gaps	Surface pressure mark / surface quality	Fibre orientation / fiber ankle	Surface contamination	Curing / cross-linking	Cross-linking consistance	Filled resin domes	Dense resin domes	Geometric deformation	Occurrance pure resin areas	Component thickness	Component weight	Component dimension	Fibre matrix connection	
Strength requirement	5	●	◑	●	◕	●	◑	◕	◕	●	◕	◑	●	○	●	◑	○	○	◔	○	◕	○	◔	●	
Dimensional accuracy	5	◑	◔	◑	◔	◑	○	○	●	●	◑	◔	●	◔	◕	◑	○	○	●	○	●	○	●	○	
Fixation point accuracy	1	◕	◑	●	◕	●	◕	◑	●	●	◔	●	○	◕	◔	◔	○	○	○	○	○	○	○	○	
Vehicle specification	5	○	○	◔	◔	◔	○	○	○	●	○	○	○	◔	◔	◔	◑	○	●	○	◑	○	●	○	
Surface quality	3	○	○	●	◔	○	◔	◔	○	◔	○	◔	○	◕	○	○	○	◑	◑	◑	◕	◕	●	◑	Sum
Absolute Significance		33	17	51	31	39	16	20	39	67	26	22	40	22	41	26	10	6	51	6	54	9	57	26	709
Relative Significance [%]		5	2	7	4	6	2	3	6	9	4	3	6	3	6	4	1	1	7	1	8	1	8	4	
Ranking		10	18	4	11	8	19	17	8	1	12	15	7	15	6	12	20	22	4	22	3	21	2	12	

Figure 5. Evaluation of the first stage – requirements and defects/features.

The classifying again is based on the ranking of the process parameters in the second stage. So the mixing quality and amount of resin receive the highest classification of 5, the constancy of the impregnation 3 and the airless impregnation is valued with 1. In the detail analysis can be seen that the interactions between the high rated process parameters are limited to a few detail parameters such as the pressure setting of the dosing system or the stack permeability. In comparison for the process parameters with a lower classification, there are strong interactions between a lot of different detail parameters. That means they are harder to control and this fact is also reflected in the evaluation of the implementation difficulty in the second stage.

The advantage of the assessment in a team of experts is the opportunity to discuss about additional interactions among the process parameters themselves, which can be verified in the analysis of real process data.

There is also the possibility to evaluate the difficulty of altering a process variable. Even if several factors have been evaluated with a very high significance, there are obvious differences in the implementation of process changes. For example, the ambient conditions in a production hall are more difficult to change than the temperature of the tool since this would require complex reconstruction work. In comparison, the tool temperature can be changed easily by a simple adjustment in the press setting. For this purpose, five levels have been introduced which reach from 1 – easy to change to 5 – not feasible. For process improvement measures, derived from the matrix, it is useful to start with the variation in very critical factors with a low implementation difficulty before more complex change measures are realised.

Conclusion of the theoretical approach

Using the theoretical approach, the requirements of fibre reinforces plastic parts have been defined in the first step. Continuative features, which affect the quality or properties of the components, have been structured to be included in the evaluation process. Material properties and process variables, which affect the component characteristics, have been identified by the 6M method as well. During the matrix generation and evaluation unimportant factors have been sorted out. By the evaluation of the interactions within a team of experts, the relations among process parameters and feature formation have been analysed as well as the effect of features on the components (Figure 8).

As the assessment of the conditions matrix generates a ranking of the most critical factors, it can be used as a ranking for the implementation of process improvements. The estimation of the changing effort enables a structured approach for the process improvement, which provides first steps with little effort. Only when

Defects/Features	Classifying / Process parameters	Stack		Resin				Pressing			
		Layer slippage	Contamination fiber material	Constant impregnation	Impregnation free from air	Resin amount	Mixing quality resin	Maximum pressure	Temperature top mold	Temperature bottom mold	
Cross folds / strong waviness / locks	3	●	○	◔	○	◔	○	○	◑	◑	
Longitudinal folds	1	●	○	○	○	○	○	○	◑	◑	
Laid open fibers / dry spots	5	◑	◑	●	○	●	◔	◑	○	○	
Pores / foamy areas / defects	1	◔	◕	●	◕	●	◕	◑	◑	◑	
Air locks / air gaps	3	◔	○	●	◑	●	◕	◑	◑	◑	
Residue / entrapments component	1	○	○	○	○	○	◑	○	○	○	
Residue / entrapments environment	1	○	●	○	○	○	○	○	○	○	
Inhomogene material areas	3	●	●	◑	○	◑	●	◕	○	○	
Cracks	5	◑	○	○	○	○	●	○	◑	◑	
Gaps	3	◕	◔	◔	○	◔	○	◔	◑	◑	
Surface pressure mark / surface quality	3	○	◑	◔	○	◔	◔	○	○	○	
Fiber orientation / fiber ankle	5	◑	◔	◔	○	◔	○	○	◑	◑	
Surface contamination	1	○	◕	○	○	○	◕	○	○	○	
Curing / cross-linking	5	○	◑	○	○	○	●	○	◕	◕	
Cross-linking consistance	3	○	◑	◑	◔	○	●	○	◕	◕	
Filled resin domes	1	○	○	◑	◑	●	◑	○	◑	◑	
Dense resin domes	1	○	○	◑	◑	●	◑	○	◑	◑	
Geometric deformation	5	○	○	○	○	◕	◕	○	◔	◔	
Occurrance pure resin areas	1	○	○	◑	◑	●	◑	○	◑	◑	
Component thickness	5	◔	◔	◑	○	●	◔	●	◑	◑	
Component weight	1	○	◔	○	○	●	◔	●	◑	◑	
Component dimension	5	○	○	○	○	○	○	○	○	○	
Fiber matrix connection	3	○	◕	○	◔	○	●	○	○	○	Sum
Absolute Significance		76	77	78	21	107	128	54	89	89	3188
Relative Significance [%]		2	2	2	1	3,4	4	2	2,8	2,8	
Ranking		12	11	10	54	3	1	29	6	6	
Implementation difficulty		5	2	4	5	2	1	1	2	2	

Figure 6. Cutting of defects/features and process parameters for parameter analysis.

these do not show any profit, elaborate steps will be considered in order to keep the time and cost factor low.

The results show that not individual factors but rather the interaction of several influencing parameters form clusters. In particular factors that affect the properties and processing method of the resin system have a decisive influence on the component quality equivalent to the highest significance. As concrete process parameters the mixing ration of resin and hardener and the resin amount – in summary the parameters of the resin system – may be mentioned. The next position in ranking is occupied by parameters concerning the tool and pressing process. These include the tool geometry and temperature as well as the pressing profile. As a third major group, the properties and quality of the semifinished fibre material are mentioned. Therefore, the slippage and orientation of the fibre layers play an important role.

Further procedure

The gained insights into the critical factors and approaches to their interactions can now be used as

Process Parameters	Classifying / Parameter Detail	Stack quality	Stack permeability	Absorption capacity roving	Resin temperature	Viscosity	Density adjustment	Infiltration time	Pressure setting dosing	Resin application model	Application layer	Environment conditions	
Constant impregnation	3	●	●	●	●	●	●	●	◕	●	●	◕	
Impregnation free from air	1	●	●	●	●	●	○	●	◕	●	●	◕	
Resin amount	5	○	◑	◔	○	○	◑	○	◕	○	○	◑	
Mixing quality resin	5	○	○	○	◕	◕	●	○	◕	○	○	○	Sum
Absolute Significance		16	26	21	16	16	22	16	27	16	16	22	252
Relative Significance [%]		6	10	8	6	6	9	6	11	6	6	9	
Ranking		6	2	5	6	6	3	6	1	6	6	3	
Implementation difficulty		4	2	4	1	4	1	1	2	2	1	4	

Figure 7. Cutting of detail analysis impregnation process.

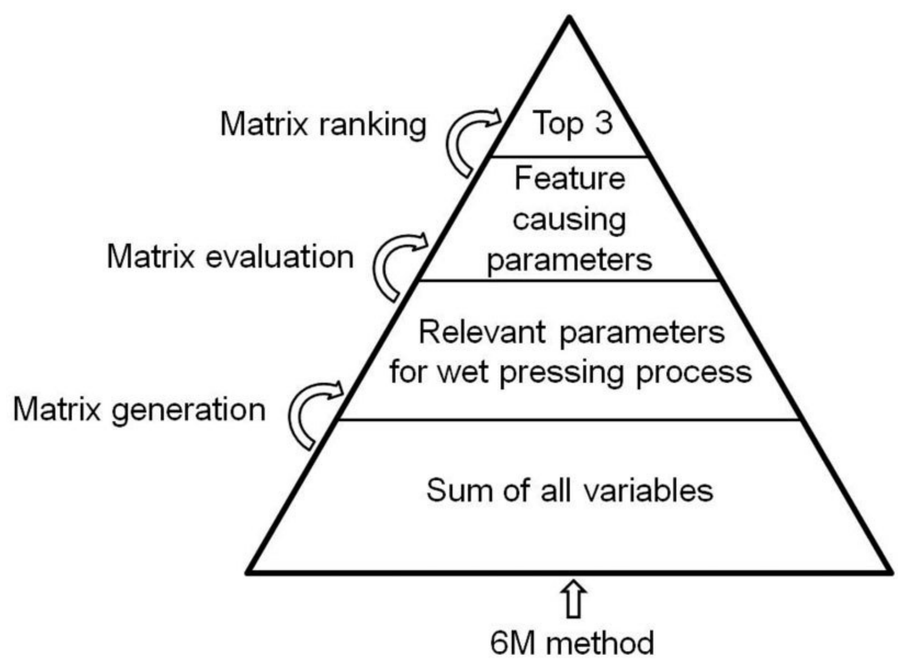

Figure 8. Stepwise method to identify the most critical influences.

an information base for the analysis of real process parameters like described in a continuing article. In detail, the recording and preparation of process data in an early phase of process implementation is described. For the three key aspects resin system, pressing process and semi-finished fibre part quality, for instance, the following process parameters are considered:

- Stack weight and storing duration.
- Resin amount, component temperatures and infiltration time.

– Pressing force/maximum pressure, sequence and tool temperatures.

During the data analysis, the potential of the theoretical approach is estimated concerning its applicability to real processes.

Declaration of Conflicting Interests

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References

1. Bel S, Hamila N, Boisse P, et al. Finite element model for NCF composite reinforcement preforming: importance of inter-ply sliding. *Composites A: Appl Sci Manuf* 2012; 43: 2269–2277.
2. Dong L, Lekakou C and Bader MG. Solid-mechanics finite element simulations of the draping of fabrics: a sensitivity analysis. *Composites A: Appl Sci Manuf* 2000; 31: 639–652.
3. Leclerc JS and Ruiz E. Porosity reduction using optimized flow velocity in resin transfer molding. *Composites A: Appl Sci Manuf* 2008; 39: 1859–1868.
4. Gupta A and Kelly P. Optimal Galerkin finite element methods for non-isothermal liquid composite moulding process simulations. *Int J Heat Mass Transfer* 2013; 64: 609–622.
5. Villière M, Lecointe D, Sobotka V, et al. Experimental determination and modeling of thermal conductivity tensor of carbon/epoxy composite. *Composites A: Appl Sci Manuf* 2013; 46: 60–68.
6. Shojaei A. A numerical study of filling process through multilayer preforms in resin injection/compression molding. *Composites Sci Technol* 2006; 66: 1546–1557.
7. Liu X. Isothermal flow simulation of liquid composite molding. *Composites A: Appl Sci Manuf* 2000; 31: 1295–1302.
8. Pillai KM, Tucker CL III and Phelan FR Jr. Numerical simulation of injection/compression liquid composite molding. Part 1. Mesh generation. *Composites A: Appl Sci Manuf* 2000; 31: 87–94.
9. Pillai KM, Tucker CL and Phelan FR. Numerical simulation of injection/compression liquid composite molding. Part 2: preform compression. *Composites A: Appl Sci Manuf* 2001; 32: 207–220.
10. Mohammed U, Lekakou C and Bader MG. Experimental studies and analysis of the draping of woven fabrics. *Composites A: Appl Sci Manuf* 2000; 31: 1409–1420.
11. Lawrence JM, Hsiao K, Don RC, et al. An approach to couple mold design and on-line control to manufacture complex composite parts by resin transfer molding. *Composites A: Appl Sci Manuf* 2002; 33: 981–990.
12. Sozer EM, Bickerton S and Advani SG. On-line strategic control of liquid composite mould filling process. *Composites A: Appl Sci Manuf* 2000; 31: 1383–1394.
13. Trochu F, Ruiz E, Achim V, et al. Advanced numerical simulation of liquid composite molding for process analysis and optimization. *Composites A: Appl Sci Manuf* 2006; 37: 890–902.
14. Cavallini C, Giorgetti A, Citti P, et al. Integral aided method for material selection based on quality function deployment and comprehensive VIKOR algorithm. *Mater Des* 2013; 47: 27–34.
15. Zhang F, Yang M and Liu W. Using integrated quality function deployment and theory of innovation problem solving approach for ergonomic product design. *Comput Ind Eng* 2014; 76: 60–74.
16. Verband der Automobilindustrie e. V. (VDA). Teil 3: QFD. In: Anonymous (ed). *Qualitätsmanagement in der Automobilindustrie – Sicherung der Qualität in der Prozesslandschaft*. 1 ed. VDA: Berlin, 2008.
17. Kuster J. 3.4.3 Ursachen-Wirkungsanalyse (Fischgräten-Methode). *Handbuch Projektmanagement*. 3rd ed, 2011, p. 401.