

Original Research

Reducing Laboratory Test Waste in the Coating Development Process

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Abstract

The article proves the possibility of reducing the negative environmental impacts that arise in the new coating development by redesigning the process and implementing modern informational technologies. Environmental standards in the coating industry are becoming strained, but at the same time the market requires products that provide better protection. In new product development, the key factor is efficiency as it is important to develop a new product in the shortest possible time with the lowest costs. The development process is carried out with a laboratory testing a large number of formulations relatively early while only a few of them meet technical requirements. They are also often not economically viable or acceptable from an environmental point of view. Using the innovative information solution, process workflow was improved. By obtaining data from cloud databases, the environmental relevance as well as the price acceptability of each formulation can be checked, even before the laboratory tests were carried out. Consequently, only those formulations that were environmentally and cost suitable were tested. In this way, the number of laboratory tests were significantly minimized, and consequently amounts of waste were reduced to a minimum.

Keywords: sustainable formulation, hazardous waste, coatings development, business process redesign, digitalization

Introduction

Manufacturers in the coating industry are faced with challenges of increasing magnitude. On the one hand, customers are demanding coatings that ensure ever more effective protection of the substrate but, at the same time, meet the relevant aesthetic criteria (brilliance, colour, etc.). On the other hand, environmental protection requirements are being tightened constantly.

Therefore, the use of some substances that increase the effectiveness of coatings are being discontinued or heavily restricted [1, 2]. The third important aspect is, of course, economic: a manufacturer has to have the price of a product in mind all the time. Optimising these factors when developing a product is an extremely demanding task; moreover, manufacturers are faced with heavy competition. For example, in the EU-28 in 2016 there were 3,865 companies involved in the manufacture of paints, lacquers and related coatings, printer inks and body fillers [3].

Coatings, like some other products (e.g., cleaning agents and personal care products), require relatively complicated formulations consisting of ingredients'

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various classes. Preparing formulation should involve environmental friendliness and health safety as well as affordability of ingredients. So-called environmentally friendly (often designed as “green” or “sustainable”) ingredients should have a lower degree of environmental or health risk than known alternatives [4]. The coating industry also has to follow trends in modern production where it is of increasing importance to optimize the degree of materials and energy utilization and to minimize the environmental impact [5-7]. Because the waste generated in the coating industry includes a considerable share of hazardous waste and the principle of waste minimization is particularly important [8]. Sustainable production now has many possibilities because of the development of informational technology with cloud databases [9].

Advances in nanotechnology have had a very great impact on the coatings development in recent years, as the use of nanoparticles enables specific coatings to be given certain specific attributes that the use of micrometric particles cannot give them. From the environmental aspect, one of the main requirements is for the use of hexavalent chromium compounds to be abandoned because of their toxicity and carcinogenicity [10-13]. Coatings containing hexavalent chromium provide excellent anti-corrosion protection. Consequently, it is difficult to replace hexavalent chromium compounds with other substances. This presents manufacturers with a considerable challenge. The use of hexavalent chromium has already been heavily restricted in recent years throughout the world, although there are still allowances made for highly sensitive aircraft parts. European regulations restrict the use of hexavalent chromium compounds in conversion coatings to a maximum 0.1% by weight, and the requirements are getting ever stricter in the US [13, 14]. Similarly, there are restrictions of cadmium and cyanide use in the production of coatings [15]. Another emphasized problem in the coatings industry is volatile organic compounds' (VOC) emissions [16-19]. There has been a noticeable trend over the last few years in the use of water-based solvents in place of organic solvents. Therefore, as stated in Phulpoto et al. [20], the worldwide production of industrially applied paints increased from 6,3 million tons in 1980 to 10,5 million tons in 2006 (67% increase). Meanwhile, the consumption of solvents in the same period rose only from 4,1 million tons to 4,2 million tons (2,5% increase). Also, great advances have been made in the development of water-based solvents, although a compromise must be sought between environmental protection and price aspects [13, 21-24].

According to Partidário and Vergragt [25], paint (coating) chain consists of the following phases: 1) Production and supply of raw materials, 2) Paint (coating) production, 3) research and development (R&D), 4) Coating applications, 5) Use of a product protected by coating and 6) Waste management (end of life product disposal or recycling). The environmental

problems and principles of sustainability are taken into consideration when raw materials and coatings are being manufactured and used (application of a coating on a substrate) and when products are being used and disposed of once they reach the end of their useful life. There is particular emphasis on exposure of workers to harmful atmospheres during the production and application of coatings [13, 25]. However, as the entire lifecycle of a product has to be taken into account when examining the environmental aspects, any examination of environmental impact cannot ignore the R&D phase. As the number of requirements regarding the quality and aesthetic criteria of coatings is increasing all the time, the development process is becoming more and more complex. The development of such products also includes a considerable amount of laboratory work, from the synthesis and mixing of ingredients to the testing of the effectiveness and durability of coatings. With coatings having to ensure effective protection for as long as possible, laboratory testing often takes place under strict conditions that require the use of certain aggressive chemicals. It is therefore clear that laboratory activities also cause significant changes to the environment. In practice, it is often the case that a coating that has successfully passed a long series of laboratory tests does not meet contemporary environmental protection standards on account of its composition. Therefore, it would make sense to check in advance whether the composition proposed for a coating meets environmental protection standards applying to a certain market. This would avoid laboratory procedures that, in addition to taking time and incurring costs [26], also produce considerable amounts of waste [27] that can be classified as hazardous. In any case, modern guidelines on waste have to be followed. These prioritise the prevention of waste formation or the reduction in the amounts of waste produced, according to the concepts of ZERO waste and eco-efficiency [28-35].

These questions were also asked when the coatings development process was studied. The research purpose was to investigate whether the process can be rationally improved (according to the above requirements) using cloud-based information technology and a “big data” approach. In order to carry out the research, a research sample of several companies involved in the production of coatings was selected. A group of small and medium-sized enterprises was included in the sample. All these enterprises perform the development process in a conventional manner – without the use of information technology, which would enable digital transformation.

In the future it will be most important to pay considerable attention to the concepts of sustainability in the phase of product development [36-38]. Therefore, the present paper describes an example of process redesign, which will contribute to the higher degree of process sustainability. Section 2 describes the coatings development process and research procedure while

section 3 presents results and discussion of the research. Section 4 concludes the article.

Methods

Process of Coatings Development (as a Research Fundamental)

As has already been mentioned, the development of new products in the coatings sector is becoming increasingly more complex as the products have to meet a raft of requirements. A coating contains a series of ingredients: resins, additives, pigments, fillers, catalysers, solvents, etc. Because the number of possible ingredients that can be included in the formulation is very large, the systems by creating a new coating are quite complex [39, 40]. As C. Bramlage illustrates in Coatingstech's reference [41], assuming the manufacturer can choose from 10 different resins, 10 pigments, 10 catalysers and 10 additives, this represents 10,000 different combinations from a qualitative viewpoint only. In addition, there exist variations in the ratio of quantities of the individual ingredients. The use of information technology is therefore becoming more or less indispensable in the product-planning process. Cole and Hughes [12] point out that three technologies or approaches have become established in the production of anti-corrosion coatings since 2005: high-flow studies, multiscale modelling and self-healing coatings. Multiscale modelling (MSM) enables a fairly accurate forecast of the properties and useful life of coatings, and therefore makes virtual planning possible. Self-healing is based on the ability of a coating to renew or repair itself. This is the safest method, as errors and damage can never be ruled out. High-flow experimentation enables a large number of tests to be carried out at the same time. Chemically very similar ingredients that differ from each other only minimally in terms of molecular structure can also be tested [12]. Manufacturers are placing considerable emphasis on developing state-of-the-art laboratory equipment that, with the help of automation and robotisation, enables a large number of tests to be performed in a short time. In this way, laboratory equipment systemically checks a large number of ingredients under variable conditions [40].

Because of requirements in coating products, the coatings industry has following the lead of other industrial sectors (such as pharmaceuticals), which have begun to develop high-flow systems that incorporate computer simulation [39, 42-44]. The development of laboratory equipment increases test speeds and thereby enables a higher number of measurements performed in a specific period. While this helps to reduce the amount of time spent on the product development process, technological development is not enough on its own. It is very important to estimate the environmental and health hazards of a product from the ingredients hazard

data at the stage of formulation preparation [45]. Modern information technology offers great opportunities for improvement as it enables processes to be streamlined to a considerable extent [26, 46].

According to the conventional way of working, manufacturers frequently prepare a large number of potential products and then test them in the laboratory. Products that prove to be suitable from a technological point of view (they provide good protection to the substrate, meet aesthetic criteria, etc.) then become eligible to be incorporated into the regular manufacturing process and placed on the market.

Research Procedure

We found that significant progress in the coatings' R&D process can be made by innovative information and communication technologies (ICT) combined with a digitalization approach [47].

A process analysis is necessary for digital transformation of the coatings' development process. This requires acquisition of relevant and up-to-date data, development of adequate process models and selection of a "technological enabler" [48]. Targeted interviews were used for acquisition of process execution data.

Process models in the adequate repository are necessary for business process analysis and redesign. As ARIS methodology presents a user perspective of the process [49-51], it was found to be the most appropriate tool for modeling. The event-driven process chain (EPC) model type was used. The EPC model is based on the logic that an event triggers an activity (or several activities). Therefore, a particular activity ends with a new event or with several events. Business objects and relations were designed by standard symbols [52].

For a complete analysis, it was necessary to obtain data on the number of necessary laboratory test repetitions for a successful realization of coating development. Depending on the purpose of the research, data on the waste amounts generated during laboratory tests were also obtained.

The main purpose of the process redesign is to rationalize the number of tests performed in laboratory. This can be achieved when instant and free access to structured data bases of ingredients is given to the formulator. These data bases should exist in a digital form in a cloud and contain up-to-date and precise data on a large number of ingredients (resins, pigments, catalysts and additives). In such a way, the formulator will be able to prepare in real time a coating formulation that will be acceptable from the viewpoint of functional relevance, health suitability, environmental acceptance and affordability. The advantage of the redesign is that when composition of the formulation is known, all necessary documentation (i.e., hazard labels, safety data sheets, technical data sheets) can be prepared. On the basis of this, all formulations that are not acceptable for health, environmental or economic reasons can be

excluded and thus it is possible to avoid unnecessary laboratory tests. Considerable reduction of laboratory tests will contribute to waste minimization as well as to reduced use of water and energy. In addition, a development's throughput time can be reduced and its costs can be minimized.

The necessary condition for this process redesign is the availability of a technical enabler. Such a technical enabler already exists and is used as an information tool of the 4th generation [53]. This tool is at the stage of prototype testing. According to the present research, it is the only all-in-one tool that enables online, real-time searching for ingredients of coatings, virtual formulation of coatings and preparation of digital technical and safety data sheets.

The proposed process redesign was implemented in the selected company. Based on the obtained results, its suitability was checked.

Results and Discussion

Analysis of the Existing Coating Development Process

Different development processes can be basically classified into two categories: conventional process (new product development without ICT support) and new product development process with ICT support and the use of a local database.

In Table 1 and Fig. 1, results of process activities analysis are shown: data on their execution probability, average number of repetitions and waste formation.

Table 1 shows that waste is generated in product laboratory testing, external validation and internal validation.

Regarding the aim of the research (to analyse the possibility of reducing waste in the new coating development process), data on the amounts of waste generated by individual companies in the execution

Table 1. Key activities of the existing new coatings development process.

New coatings development process				
##	Process activities	Probability ^a	Average number of repetitions ^b	Waste formation
10	Creating a new product idea	0,06	0,14 ^c	
20	Market analysis of existing products	1,00	2,29	
30	Searching for suitable binders	0,92	2,29	
40	Study of binders properties	1,00	2,50	
50	Searching for pigments	0,19	2,50	
60	Searching for additives			
70	Searching for solvents			
80	Searching for fillers			
90	Formulation (modified) formulations	1,00	13,33	
100	Ordering samples	1,00	13,33	
110	Product laboratory testing	0,50	13,33	Yes
120	Product parameters measurement	0,40	6,67	
130	Product hazard identification			
140	Product price calculating			
150	Internal validation	0,50	2,67	Yes
160	External validation	0,75	1,33	Yes
170	Preparation of documentation draft	1,00	1,00	
180	Creating documentation	1,00	1,00	

^a The probability of executing an individual activity according to the decisions during the process. With the exclusion of activity "10", there exists probability that the activity is included in the process. Probabilities for activities that are running parallel (simultaneously) can be found in merged fields.

^b The average number of each activity repetitions for the one product development is given. It is calculated on the basis of data on the number of each activity execution repetitions and the number of developed products in selected companies in 2018

^c Because the process has several potential start-events, the activity "Creating a new product idea" is rarely performed.

In approximately seven cases of developed products, only once did the idea for a new product arise in this activity. Other ideas are given by other stakeholders; ingredient/binder supplier or customer can request for new product or for product modification.

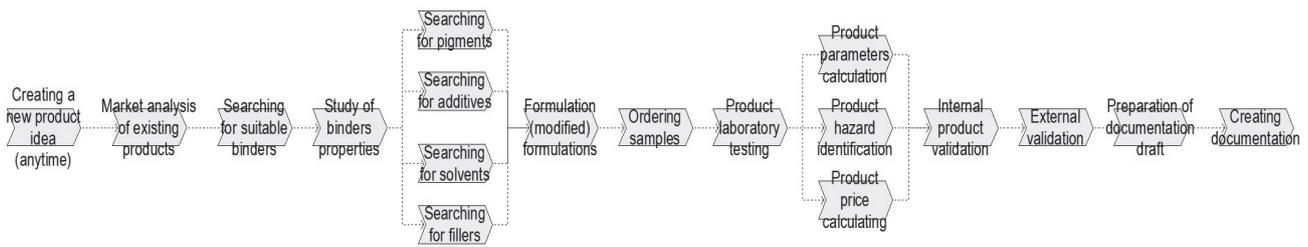


Fig. 1. Model overview of the existing new coatings development process.

of laboratory testing of each coating pattern were obtained.

In the research, the amounts of material used during laboratory tests were not explicitly measured. Therefore, savings can be accurately provided only in percentages as absolute values were estimated only on the basis of assumptions. It is assumed that the average amount of ingredients in one sample is between 0.25 and 2.5 kg. Therefore, for a calculation of waste reduction, 1 kg of waste may be considered on average to be generated in one test sample. In one execution of laboratory testing, 20-50 samples are prepared and tested. Therefore, for a calculation of waste reduction, 35 samples may be considered as the average number of samples.

The following formulas were used to calculate the generated waste in the development process of one coating:

$$m_s = \sum_{i=1}^n m_i \tag{1}$$

m_s - mass of waste
 m_i - mass of individual ingredient's waste
 n - number of ingredients in the proposed formulation

$$m_t = \sum_{j=1}^m \sum_{i=1}^n m_i \tag{2}$$

m_t - mass of waste formed in individual laboratory testing for a group of formulations
 m_i - mass of an individual ingredient's waste
 n - number of ingredients in the proposed formulation
 m - number of formulations in a particular generation

$$m_p = \sum_{k=1}^p \sum_{j=1}^m \sum_{i=1}^n m_i \tag{3}$$

m_p - mass of waste formed at the new product development process
 m_i - mass of an individual ingredient's waste
 n - number of ingredients in the proposed formulation
 m - number of formulations in the group
 p - number of testing generations

Based on the obtained data and assumptions and formulas noted above, we calculated that the average amount of waste in the new product development process is 467 kg.

Proposal of the Coatings Development Process Redesign

Not uncommonly, a product that has passed the exacting testing phase and shown itself to be technologically suitable (effective, durable, etc.) is shown not to meet environmental and health standards. The cause is unsuitable composition — which could have been established at the initial stage. The laboratory testing phase could therefore have been avoided for saving time, materials and energy. This gives rise to considerable costs and, as is particularly highlighted in this paper, certain amounts of waste, some of which can be classified as hazardous.

The solution of shortening the development processes is therefore known. In order to implement the solution, the formulator needs data on the large number of potential ingredients at the start of the development process. In principle, this data can be obtained. It can be found on technical information documents, safety documents and ingredient price lists provided by manufacturers. The data is publicly available. It can be obtained most often on the basis of a request together with an ingredient sample. As a rule, the data comes in the form of paper documents or electronic documents in pdf format.

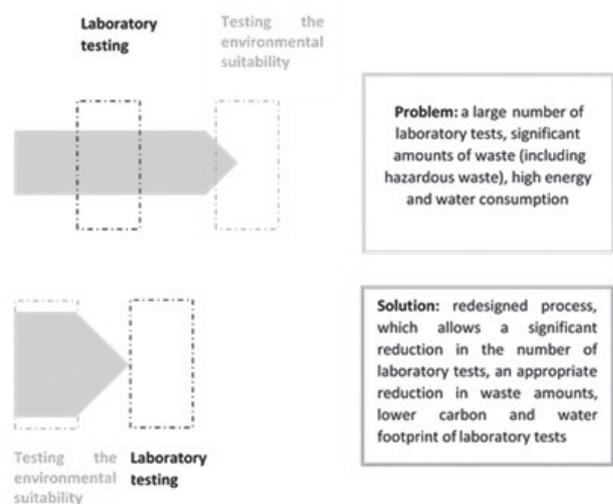


Fig. 2. Schematic comparison between the a) conventional and b) redesigned processes.

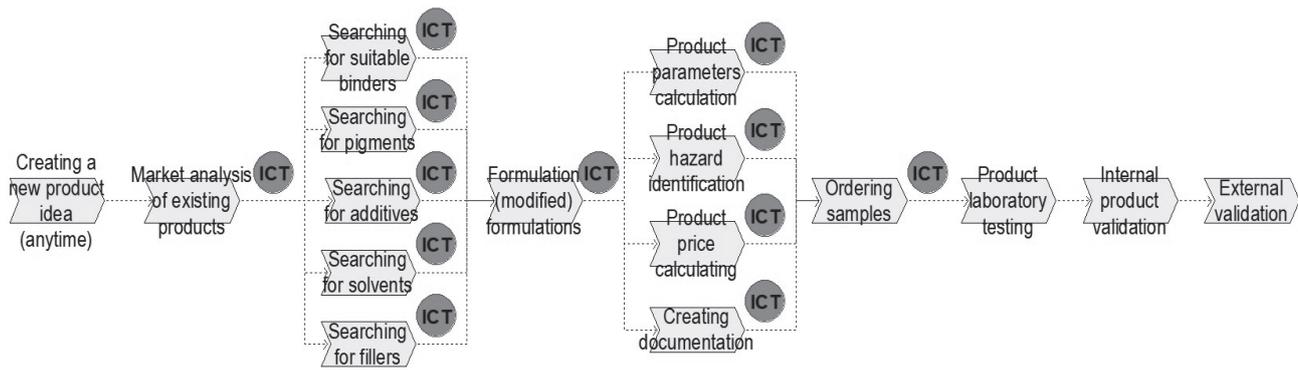


Fig. 3. Model overview of the modified (redesigned) new product development process with ICT support and the use of a cloud-based database.

This is where the problem arises. Obtaining this data is usually a more difficult and more protracted process for the formulator than laboratory testing. If we want to obtain all the data for a large number of potential ingredients, this would take more time than is available

for the coating development. Even if a company that develops and manufactures coatings creates its own collection of documents on ingredients (something companies indeed generally do), a further problem arises: the data, particularly price data, on a specific

Table 2. Key activities of the new product development process with ICT support and the use of a cloud-based database.

New product development process with ICT support and the use of a cloud-based database				
##	Process activities	Probability ^a	Average number of repetitions ^b	Waste formation
10	Creating a new product idea	0,06	0,07 ^c	
20	Market analysis of existing products	0,92	1,15	
30	Searching for suitable binders	0,19	1,25	
40	Searching for pigments			
50	Searching for additives			
60	Searching for solvents			
70	Searching for fillers			
80	Formulation (modified) formulations	1,00	6,67	
90	Product parameters calculation	0,80	6,67	
100	Product hazard identification			
110	Product price calculating			
120	Creating documentation			
130	Ordering samples	1,00	5,33	
140	Product laboratory testing	0,50	5,33	Yes
150	Internal validation	0,50	2,67	Yes
160	External validation	0,75	1,33	Yes

^a The probability of executing an individual activity according to the decisions during the process. With the exclusion of activity “10”, there exists probability that the activity is included in the process. Probabilities for activities that are running parallel (simultaneously) can be found in merged fields.

^b The average number of each activity repetitions for the one product development is given. It is calculated on the basis of data on the number of each activity execution repetitions and the number of developed products in selected companies in 2018

^c Because the process has several potential start-events, the activity “Creating a new product idea” is rarely performed. In approximately 14 cases of developed products, only once did the idea for a new product arise in this activity. Other ideas are given by other stakeholders; ingredient/binder supplier or customer can request for new product or for product modification.

Table 3. Results of the new product development process without ICT support and results with ICT support and the use of a cloud-based database.

New product development process without ICT support (the conventional process)					
##	Process activities (with waste formation)	Average number of repetitions ^a	Number of samples	Waste / sample [kg]	Waste / activity [kg]
110	Product laboratory testing	13,33	35	1	466,55
150	Internal validation	2,67	1	1	2,67
160	External validation	1,33	1	1	1,33
Total waste for one successful product development:					470,55
New product development process with ICT support and the use of a cloud-based database					
##	Process activities (with waste formation)	Average number of repetitions ^a	Number of samples	Waste / sample [kg]	Waste / activity [kg]
140	Product laboratory testing	5,33	10	1	53,33
150	Internal validation	2,67	1	1	2,67
160	External validation	1,33	1	1	1,33
Total waste for one successful product development:					57,33
					Waste reduction [%]
					87,82

^a The average number of each activity repetitions for the one product development is given. It is calculated on the basis of data on the number of each activity execution repetitions and the number of developed products in selected companies in 2018.

ingredient changes over time in response to supply and demand, while the documents in local document collections remain unchanged.

Therefore, the problem cannot be solved through the collection of documentation, even if that documentation is in electronic form. A solution is only possible with the use of original data on ingredients, freely available to the formulator and kept up to date. Therefore, a question arose whether there exists such a solution that would enable the digital transformation of the coatings development process.

After examining and analysing the providers of information solutions for the coatings industry, it has been found that a solution of this type already exists. However, it is not used for the purpose of shortening and simplifying development processes. Instead, it is currently being used as an online service chiefly for the production of technical information documents, safety documents and labels in the final phases of development processes. These documents are accessible in digital form so that their original data can be viewed and used. Of course, documents can be generated at any time and converted into PDF format or printed. The solution is called Allchemist [53] and has been designed to operate in the cloud. A coating's documentation is created using the data on ingredients in the standardised database, which contains technical, safety and other data on all ingredients of all products that the users of the service

have formulated up to now. The ingredients database is relatively large and increases in size with every entry made.

The solution can be used as a configurator of formulations as well. The advantage of the configurator of this type lies largely in the fact that it generates safety data alongside chemical composition, while at the same time an individual formulation is being developed. The formulator can identify the chemical properties and environmental acceptability of a formulation as it is being produced. If the ingredients also contain up-to-date information on prices, the cost of a coating can therefore be calculated in real time. The particular advantage of a development process designed in this way is that produces a large database of available ingredients that the formulator can choose without wasting time searching and gathering documents on ingredients and copying data into the formulation. This enables the formulator to produce a functionally better coating much more quickly (Fig. 2).

Results of the Redesigned Process

For the purpose of how the proposed changes impact process execution, an appropriate model of the redesigned process was developed (shown in Fig. 3). The possibilities offered by the inclusion of process support with modern ICT and the use of a cloud-based

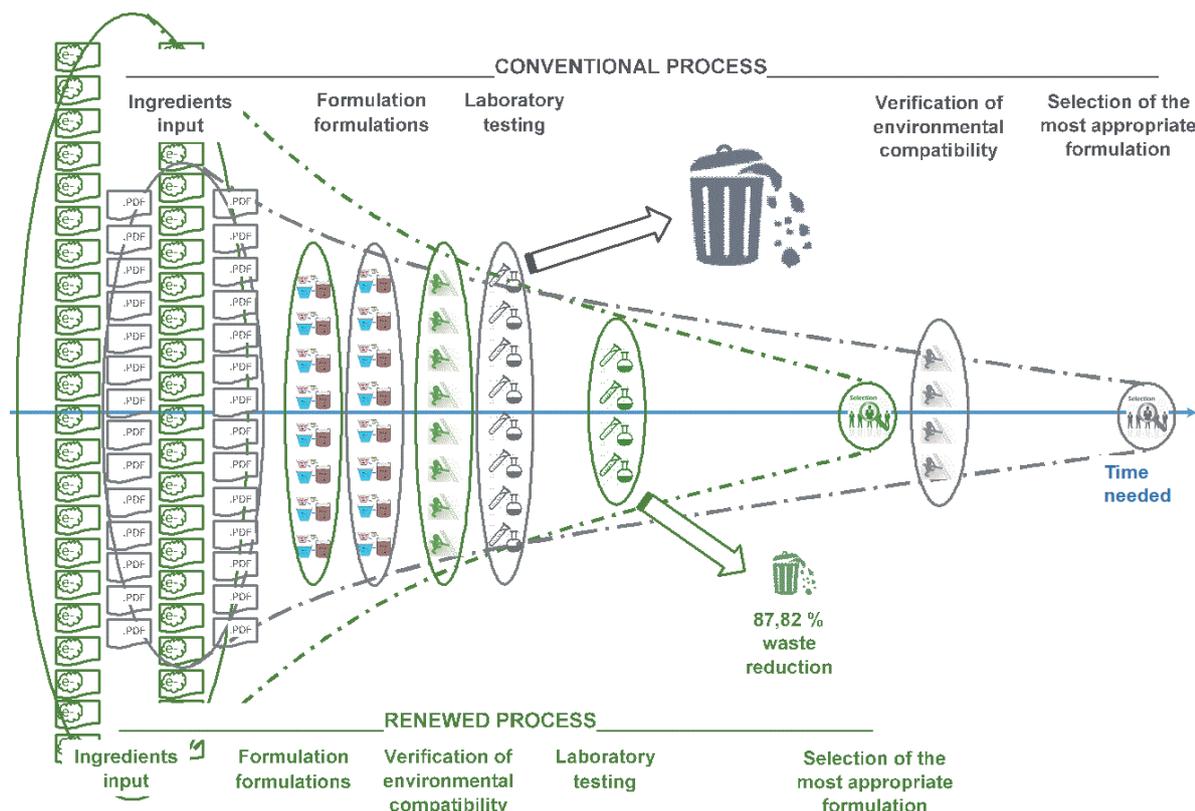


Fig. 4. Schematic presentation of the coatings development process (conventional and redesigned processes).

database have been taken into account, which allows for the inverted sequence of key activities execution in the process (Table 2). This significantly influenced on the number of laboratory tests.

The test of process was performed in a medium-sized company. This company is concerned with development and production of coating using this technical enabler [54]. The tool is used for preparation of safety data sheets in the process of new product development [55]. The company can eliminate in the first stage of the development process those formulations that are not acceptable from environmental or cost viewpoints. However, there exist certain limitations as local databases contains only data on a limited amount of ingredients.

Table 2 presents results for the new product development process with appropriate ICT support and a cloud-based database.

With the same assumption, the average amount of ingredients in one tested sample is 1 kg. In one execution of laboratory testing, due to the changed sequence of activities (preliminary digital testing of formulations), the number of samples at each test is reduced to 5-15. Therefore, for a calculation of waste reduction, 10 samples may be considered the average number. With these findings, we calculated that the average amount of waste in the redesigned development process is 53 kg.

Table 3 presents results of the research, carried out for the new product development process without ICT

support and for the redesigned process with appropriate ICT support and a cloud-based database.

In the EU-28 (2016) 3,865 companies are involved in the manufacture of paints, lacquers and related coatings, printer inks and body fillers [3]. It was assumed that each company makes at least three new products every year. Based on this, it has been estimated that reduction of waste can be assessed as between 4,000 and 5,000 tons. A schematic comparison between the conventional and redesigned process is shown in Fig. 4.

Conclusions

Based on our research, we can conclude that the redesigned process significantly cuts the number of laboratory tests. Therefore, the redesigned process causes considerably less environmental pollution because of the lower amounts of waste produced and the lower quantities of energy and water consumed. This also leads to the more sustainable process of new product development.

It is evident that the problem of development process complexity can be better resolved by reducing the number of re-tests performed in the laboratory than by shortening the periods of time spent on an individual testing procedure. This is possible only if formulations are simulated in advance and individual formulations are checked from the point of view of environmental and price acceptability. This narrows down the

number of potentially suitable formulations prior to laboratory testing. The environmental acceptability of a formulation depends on the coating's ingredients and on their respective proportions within the coating. Therefore, when a formulator has this information, then he or she can calculate the overall environmental acceptability of the coating. The same is true when it comes to calculating the cost price, which depends on the prices of individual ingredients, their respective proportions and the price attached to the technological procedure of manufacturing the coating. When this information is available, a precise calculation of the coating cost can be made. Other advantages of the redesigned process are a shorter process execution time, a greater set of available information and a technically better solution (optimal coating).

The used information solution is useful, not only for formulators or coatings manufacturers but also for ingredients suppliers, which can add up-to-date information about their products to databases.

In the field of coating development's impact on the environment, a wider research should be carried out to determine the actual amounts of waste, by individual types, that are formed. This will demonstrate the actual level of reducing the environmental load on waste by using the redesigned process. At the same time, it would be worth exploring the reduction of environmental impact due to redesign in terms of water consumption, energy and cleaning products.

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Conflict of Interest

The authors declare no conflict of interest.

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