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Institute of Logistics
Faculty of Security, Logistics and Management
Military University of Technology
in Warsaw

The use of 3D printing technology in prototypes of selected components for civil and military rail vehicles

Zastosowanie technologii druku 3D w prototypach wybranych podzespołów pojazdów szynowych cywilnych i wojskowych

Maciej Frankowski

m.frankowski@fpspозnan.pl; ORCID: 0000-0002-7867-2697
Doctoral School, Poznan University of Technology, Poland

Zbigniew Cichoński

zbigniew.cichonski@doctorate.put.poznan.pl; ORCID: 0000-0002-8743-0374
Doctoral School, Poznan University of Technology, Poland

Łukasz Stępniewski

lukasz.stepniewski@doctorate.put.poznan.pl; ORCID: 0000-0001-5889-5992
Doctoral School, Poznan University of Technology, Poland

Wojciech Sawczuk

wojciech.sawczuk@put.poznan.pl; ORCID: 0000-0002-5049-6644
Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland

Abstract. The article addresses the issue of using Rapid Prototyping (RP) technology in the design and optimization of components of modern rail vehicles, both civilian and military. Contemporary technical requirements and the specificity of the rail transport sector make the implementation of RP technology in this area a significant challenge, while at the same time opening up new design and production possibilities. The literature review revealed a significant research gap regarding the use of RP technology in the context of rail vehicles, which results from high strength requirements, rigorous safety standards,

and a limited market of recipients. The research problem focuses on the analysis of the possibilities of use of RP technology on the process of designing, verifying and implementing rail vehicle components, especially in the context of limitations resulting from traditional production methods, such as welding and manual assembly. A significant challenge is to ensure compliance between the 3D model developed in CAD systems and the actual product, which in the case of conventional processes can lead to discrepancies requiring numerous modifications at the production stage. This problem is crucial for the efficiency of designing and implementing new solutions in rail vehicles. The aim of this work is to develop and verify the concept of a roof vent for rail vehicles as a case study confirming the thesis that RP technology significantly accelerates, facilitates, and improves the process of designing and implementing rail vehicle components. The adopted methodology includes qualitative research methods that allowed simultaneous testing of two design variants of the vent owing to the use of a modular component structure. These studies allowed the assessment of the impact of RP technology on the correctness of the design and the compliance of the component with the design assumptions. Furthermore, taking into account the availability of materials that meet the rigorous requirements of the PN-EN 45545 fire protection standard, a new version of the vent was designed, optimized for 3D printing technology. The use of this technology allowed the production of a detail with complex geometry, of which the production would be technologically impossible using conventional methods due to equipment limitations. The results obtained indicate that RP can be an effective tool supporting the design and testing of components in the rail transport industry; however, due to technological limitations, it is not suitable for the production of large-size elements and large-scale serial production.

Keywords: Rapid Prototyping, Rail Vehicles, 3D Print, Additive manufacturing, Industry 4.0

Abstrakt. W niniejszym artykule podjęto zagadnienie zastosowania technologii szybkiego prototypowania (Rapid Prototyping, RP) w projektowaniu i optymalizacji komponentów nowoczesnych pojazdów szynowych, zarówno cywilnych, jak i wojskowych. Współczesne wymagania techniczne oraz specyfika sektora transportu szynowego sprawiają, że implementacja technologii RP w tym obszarze stanowi istotne wyzwanie, a jednocześnie otwiera nowe możliwości projektowe i produkcyjne. Przegląd literatury wykazał znaczącą lukę badawczą dotyczącą wykorzystania technologii RP w kontekście pojazdów szynowych, co wynika z wysokich wymagań wytrzymałościowych, rygorystycznych norm bezpieczeństwa oraz ograniczonego rynku odbiorców. Problem badawczy koncentruje się na analizie możliwości wykorzystania technologii RP na proces projektowania, weryfikacji oraz wdrażania komponentów pojazdów szynowych, szczególnie w kontekście ograniczeń wynikających z tradycyjnych metod produkcji, takich jak spawanie i montaż ręczny. Istotnym wyzwaniem jest zapewnienie zgodności między modelem 3D opracowanym w systemach CAD a rzeczywistym produktem, co w przypadku konwencjonalnych procesów może prowadzić do rozbieżności wymagających licznych modyfikacji na etapie produkcji. Problem ten ma kluczowe znaczenie dla efektywności projektowania i wdrażania nowych rozwiązań w pojazdach szynowych. Celem niniejszej pracy jest opracowanie i weryfikacja koncepcji wywietrznika dachowego dla pojazdów szynowych jako studium przypadku potwierdzającego tezę, iż technologia RP znacząco przyspiesza, ułatwia oraz usprawnia proces projektowania i wdrażania komponentów pojazdów szynowych. Przyjęta metodologia obejmuje jakościowe metody badawcze, które pozwoliły na jednoczesne testowanie dwóch wariantów konstrukcyjnych wywietrznika dzięki zastosowaniu modułowej budowy komponentu. Badania te umożliwiły ocenę wpływu technologii RP na poprawność projektu oraz zgodność komponentu z założeniami konstrukcyjnymi. Dodatkowo, uwzględniając dostępność materiałów spełniających rygorystyczne wymogi normy przeciwpożarowej PN-EN 45545, zaprojektowano nową wersję wywietrznika zoptymalizowaną pod kątem technologii druku 3D. Zastosowanie tej technologii pozwoliło na wytworzenie detalu o złożonej geometrii, którego wykonanie metodami konwencjonalnymi byłoby technologicznie niemożliwe ze względu na ograniczenia sprzętowe. Uzyskane wyniki wskazują, że RP może stanowić efektywne narzędzie wspierające projektowanie i testowanie komponentów w branży transportu szynowego, jednak ze względu na ograniczenia technologiczne nie jest odpowiednie do produkcji wielkogabarytowych elementów oraz seryjnej produkcji na dużą skalę.

Słowa kluczowe: Szybkie Prototypowanie, Pojazdy Szynowe, Druk 3D, Wytwarzanie Przyrostowe, Przemysł 4.0

Introduction

Contemporary design of rail vehicles is mainly based on computer-aided design systems – CAD. Specialized 3D programs such as SolidWorks, Catia V5, Siemens NX and Autodesk Inventor are used for this purpose. These programs, although they differ from each other in interfaces, functions or tools, work on a similar principle, namely creating three-dimensional objects using solid and/or surface modeling. The experience of companies in the industry of manufacturing and repairing rail vehicles shows that the 3D model obtained in this way does not always reflect the final product. This is caused by the production technology, which is mainly a welded structure. During welding, the material heats up rapidly, and then the resulting joint cools down, causing a reduction in the length of the joined elements, the so-called welding shrinkage. If too much heat is introduced, the material bends, causing distortion. These factors affect subsequent discrepancies during final assembly. This issue is an integral part of the rail vehicle design process, which needs to be taken into account. The rapid prototyping method is one of the solutions, which allows to refine the concept of components, taking into account the aforementioned discrepancies between the 3D model and the real product.

The aim of this work is to develop the concept of a roof vent (as an example case study) of a rail vehicle using RP technology and to conduct tests on the finished vehicle. In addition, the article analyzes the available methods of additive manufacturing and the possibilities of using 3D prints in the construction of rail vehicles. The design process taking into account the RP method is shown on Fig. 1.

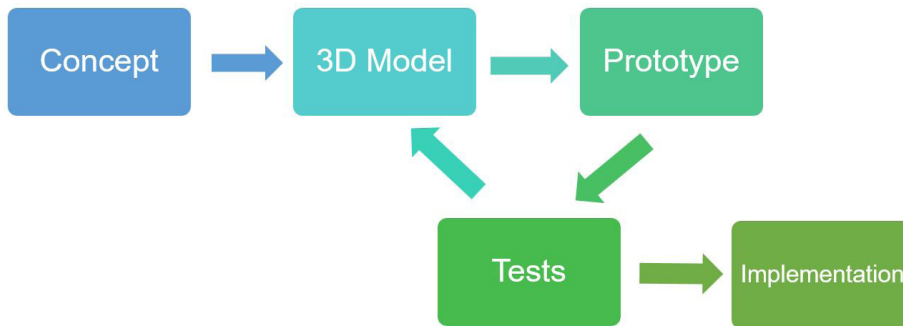


Fig. 1. Design scheme using RP technology

Source: Own study

The research problem focuses on the analysis of the possibilities of use RP technology on the process of designing, verifying and implementing rail vehicle components, especially in the context of limitations resulting from traditional production methods, such as welding and manual assembly. Therefore, a research thesis was formulated: The RP rapid prototyping technology accelerates and facilitates work related to the design of components of civil and military rail vehicles. A qualitative research approach was adopted to solve the presented problems. Additionally, participant observation was a complementary method.

Literature review

Rapid prototyping technology is used in many industries, both civilian and military (Dymyt, M., Wicewicz-Bosy, M., 2023, pp. 5-20). G. Budzik in (Budzik et al., 2009, pp. 7-16) presented the possibility of its use in the production of motor vehicle parts, such as: engine parts, drive and body components, using the 3D printing method. The RP procedure is discussed, from design in CAD systems to the production of physical prototypes. The author also presented the possibility of using 3D printing technology as a Rapid Tooling (RT) technique, i.e. a technique for rapid production of tools or casting molds. On the other hand, A. Jandyal in (Jandyal et al., 2022, pp. 33-42), M. Karbowniczek in (Karbowniczek, 2016, pp. 60-65) and T. D. Ngo in (Ngo, Tuan et al., 2018, pp. 172-196) discussed in detail the technology of 3D printing itself, focusing on an overview of available methods, materials and application in industry. In addition, in the article (Jandyal et al., 2022, pp. 33-42), the authors presented the use of this technology in industry 4.0, where the assumption of communication between machines as well as the process of machine self-learning with minimal human intervention using IoT (Internet of Things) was presented. In the articles (Ngo, Tuan et al., 2018, pp. 172-196), (Stankiewicz et al., 2023, pp. 129-148), the authors clearly present the most commonly used 3D printing methods, taking into account the type of materials used, the main applications, as well as the advantages and disadvantages of each of them. The main challenges posed to the 3D printing method were discussed, such as: high costs, limited use in large constructions and mass production, product defects, limited choice of materials. The articles (Kumar, 2003, pp. 43-47) and (Mazzoli, 2013, pp. 245-256) describe in detail the SLS method, where the authors focus on the mechanism of bonding individual layers of the created detail, as well as on the post-processing, which is characteristic of this method. In addition, A. Mazzoli in his article (Mazzoli, 2013, pp. 245-256) focuses on the use of this method in biomedical engineering, where its impact on accelerating and improving the quality of surgical procedures and implant design has been proven. The article (Vyavahare et al., 2020, pp. 176-201) adopts the author's methodology of literature analysis, on the basis of which a detailed description of

the FDM method is created. It takes into account surface treatment, dimensional accuracy, material characteristics, printing time, static and mechanical properties, costs, environmental conditions (humidity, temperature). A proposal for further development work on this method was also presented. In addition, it was pointed out that most of the research on the materials used in this method concerns ABS and PLA, which should lead to work on other materials. This was partially addressed in the paper (Wang et al., 2017, pp. 442-458) where the authors focused their attention on polymer composites in the context of 3D printing. That paper, put focus on polymer composites reinforced with particles, fibres and nanomaterials. 3D printing technology is also used in the production of railway infrastructure components. In (Fu et al., 2022, pp. 1-21) authors emphasized that this technology support design and optimization of small elements of railway infrastructure such as fastener components (e. g., clips, screw spikes and rail pads), geogrids and geocells. The 3D printing technology can also help produce sound barriers with complex geometric properties which reduce the noise caused by moving trains. Also (Toth et al., 2022) in their article presented maintenance tooling as an example of additive manufacturing in railway environment. This ability to replicate replacement components for trackside equipment on-demand eliminates the OEM's delays and reduces maintenance time. Additive manufacturing is considered as an economic approach for producing rail vehicle part because it does not require tooling investment especially when part is required in low volumes which often occurs during repairs and inspections of a railcars. A properly selected manufacturing method allows to achieve the required properties for the printed element (Muvunzi et al., 2022).

Description of selected rapid prototyping methods

The RP method is mainly used in relation to additive manufacturing methods. It is based on the creation of a physical three-dimensional object using the layer-by-layer method. However, 3D printing has found the most common application in the railway industry. In this method, the prototyping process begins with the creation of a three-dimensional model in one of the CAD programs listed in Introduction. The model prepared in this way is sent to the processing program attached to the 3D printer, where it is converted to an STL (Standard Tessellation Language) file, on the basis of which the device produces the finished printout. The sustainable aspects of 3D printing, such as less material waste and much lower costs, even when producing complex parts, make 3D printing considered the technology of the future (Jandyal et al., 2022, pp. 33-42). Thanks to 3D printers, it is possible to produce virtually any shape. However, it is important to take into account the hardware limitations, such as the size of the device's working chamber, printing time, as well as the type of technology used to produce the object, depending on its expected features and

properties. In addition to 3D printing, we distinguish the following, sample methods of RP technology: SLA (Stereolithography), SLS (Selective Laser Sintering) powder sintering, FDM (Fused Deposition Modelling) molten material deposition.

SLA stereolithography

SLA stereolithography is one of the oldest 3D printing methods, developed back in 1986, and is also considered by many to be one of the most cost-effective additive methods (Ngo, Tuan et al., 2018, pp. 172-196). It belongs to the group of 3D printing techniques that use the process of photopolymerization. The energy of the laser beam and the exposure time are the main factors influencing the thickness of each layer (Melchels Ferry et al., 2010, pp. 6121-6130). The object under construction is created as a result of selective curing of photopolymer resin with laser light. The unused resin is scraped off after the printing process is finished. The diagram of the SLA method is shown in Fig. 2.

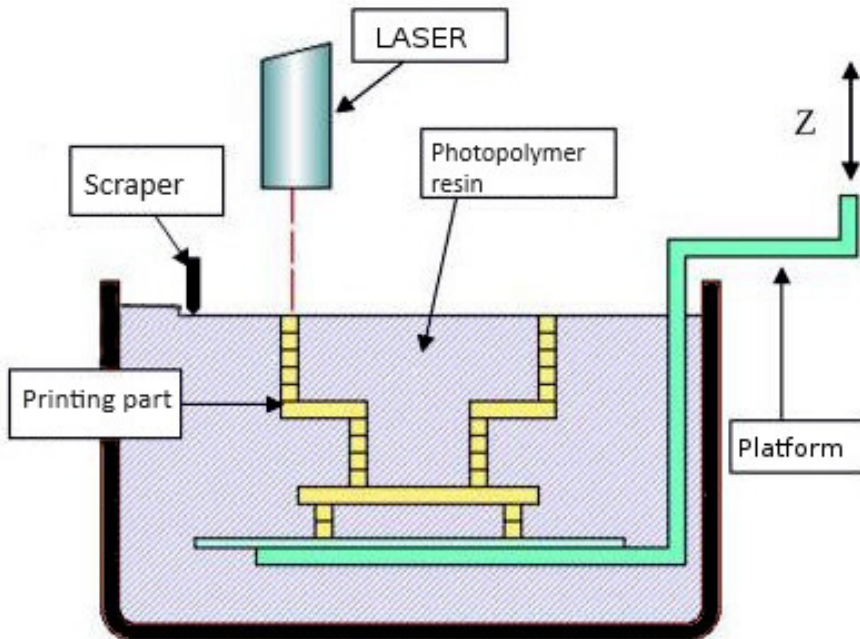


Fig. 2. SLA Technology Diagram

Source: <https://tppasp.wordpress.com/2015/05/15/sla-stereolitografia/> [Accessed: 27 May 2024]

The printed components combine very high accuracy with high surface smoothness of up to $10\mu\text{m}$ (Wang et al., 2017, pp. 442-458). On the other hand, it is characterized by a relatively long production time and high cost, as well as a limited selection of materials compatible with this method. This technology, due to the possibility of printing very precise details, is widely used primarily in medicine and dentistry as implants (Melchels Ferry et al., 2010, pp. 6121-6130) and in jewellery. It is also used for prototyping very precise and accurate models used in casting molds.

SLS powder sintering

SLS (Selective Laser Sintering) powder sintering technology is one of the basic methods of rapid prototyping, belonging to the group of Powder Bed technologies (Kumar, 2003, pp. 43-47), whose characteristic feature is the selective bonding of successive layers of powder. This method mainly uses a CO_2 laser, which sinters particles of powdered thermoplastic polymer, then combining it into subsequent layers. A diagram of this method is shown in Fig. 3.

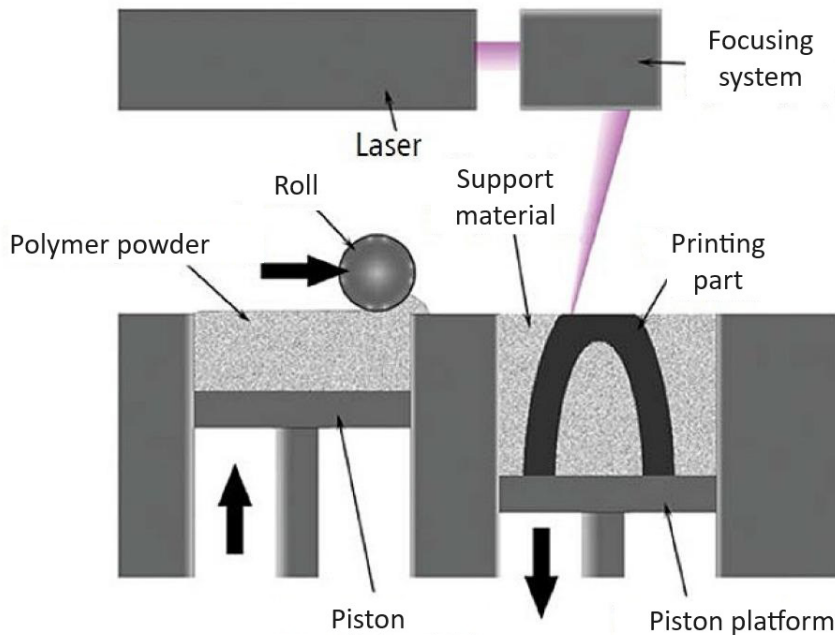


Fig. 3. SLS Technology Diagram

Source: Karbowniczek, 2016. 3D Printing Technologies

The laser can work in both continuous and pulsed mode. The working chamber is kept at a temperature just below the melting point of the powder, which significantly accelerates the sintering process (Mazzoli, 2013, pp. 245-256). The large selection of available materials is undoubtedly one of the biggest advantages of this method. These include: wax, cermet, ceramics, composites with the addition of nylon/glass fiber, metal alloys, polymers, nylon and carbides (Kumar, 2003, pp. 43-47). The main parameters that affect the finished product are the size and density of the powder, the power of the laser beam, the frequency of pulsation of the beam, and the operating temperature. SLS technology is widely used, both in prototyping and in small-batch production of functional plastic parts. Currently, among all available 3D printing technologies, it is the most frequently used method in the small-scale production of final parts of machines and technical equipment. In addition, it is also used in medicine to produce anatomical models, implants and tissue (Mazzoli, 2013, pp. 245-256).

FDM molten deposition

The FDM (Fused Deposition Modeling) technology has been known since 1988 by S. Scott Crump (Vyavahare et al., 2020, 176-201) and belongs to the group of additive techniques whose characteristic feature is the extrusion of material from printing heads. By means of electric motors, the material is taken from the spool and then delivered by means of guides to the print head (extruder), where it is heated to a semi-liquid state, as shown in the diagram in Fig. 4.

The material in this form is then placed on the work table or the manufactured element (Ngo, Tuan et al., 2018, pp. 172-196). Parts are built by deposition of successive layers of molten thermoplastic. The process of cooling the manufactured object is important in terms of the mechanics of bonding individual layers. Rapid cooling can lead to voids between the bonded layers, which affects the mechanical properties of the finished product (Vyavahare et al., 2020, 176-201). In addition, the main parameters that also affect the mechanical properties of the product are: layer thickness, width and fiber orientation (Ngo Tuan et al., 2018, pp. 172-196). Currently, FDM technology is the most widely used of all additive methods in the world thanks to its high flexibility, low price, high surface quality and, above all, the ability to produce complex shapes (Jandyal et al., 2022, pp. 33-42).

The use of 3D printing in the process of rapid prototyping of rail vehicle parts

The rapid prototyping process is discussed on the example of a roof vent installed in passenger carriages in the ventilation system that diagram of which is shown in Fig. 5.

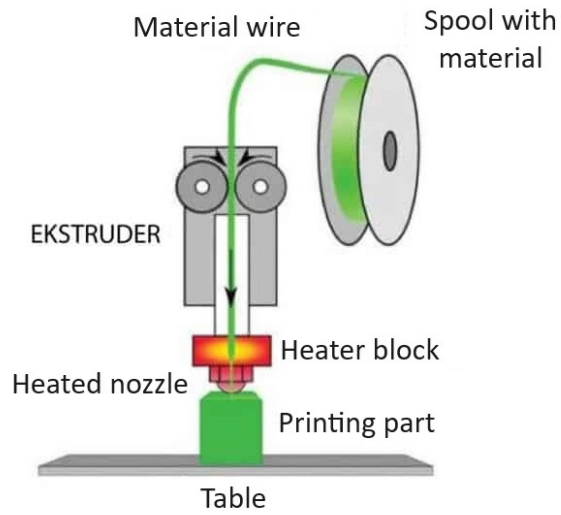


Fig. 4. FDM Technology Diagram

Source: Karbowniczek, 2016. 3D Printing Technologies

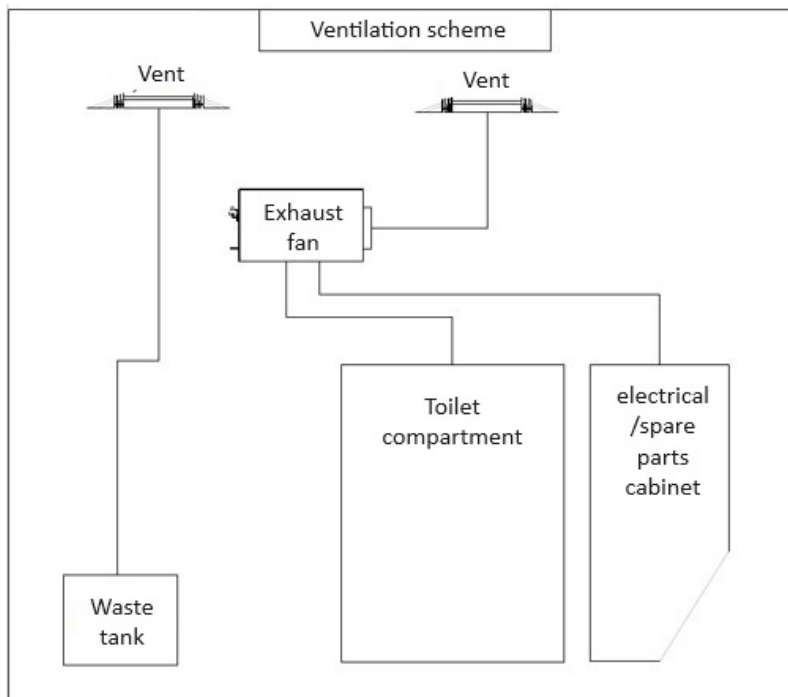


Fig. 5. Simplified diagram of ventilation system

Source: Own study

Its function is to ventilate the toilet compartments, the spare parts cabinet and the electrical cabinet, as well as the faecal tank. Due to the fact that the vent is built on the roof of the wagon as shown in Fig. 6, its shape must provide protection against the ingress of precipitation into the ventilation system during travel and standstill, while not disrupting the flow of air and gases. This is the main assumption that is set for all types of roof vents used on civil and military rail vehicles.

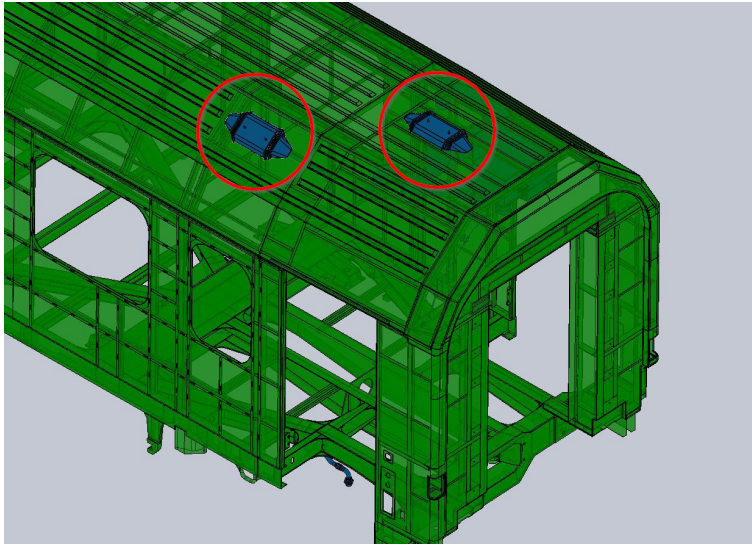


Fig. 6. Arrangement of roof vents of the TSI wagon

Source: Own study

The original vent is made of S235JR structural steel with a thickness of 1mm. As the verification of the vent assembly can be carried out during modelling in CAD programs, the verification of its functionality and compliance with the requirements for tightness is unfortunately not. Without the use of specialized programs for flow testing, it is almost impossible. However, thanks to 3D printing technology, it is very easy to make a prototype of such a vent even before the start of serial production and carry out appropriate tests on a test stand or a manufactured wagon.

Processing data for the 3D printing process

Preparing data for the 3D printing process has a great impact on the accuracy and correctness of the model obtained in the RP process. The parameters of the exported data from CAD programs should allow the execution of a physical model with the highest possible accuracy available to the RP device. Due to the elongated

shape of the vent and the thin wall, it would be very difficult to obtain the correct print, which is why the wall thickness was increased to 4mm for the purposes of 3D printing. In addition, the vent prototype consists of a fixed central part and an outer part made in two versions: the first v1 and the second v2 version. The outer parts have been deliberately differentiated in order to test two different vent concepts at the same time. The v1 version reflects the original shape of the vent end part, while the shape of the v2 version has been modified for the subsequent production of the steel element. This solution saved printing time and material by making only one prototype, which is shown in Fig. 7.

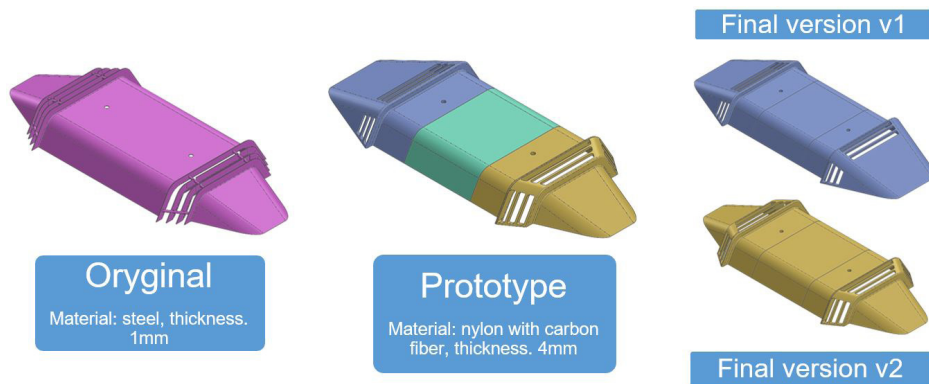


Fig. 7. Prototype of the vent in two different versions

Source: Own study

In addition, thanks to the division of the vent, the height of each parts did not exceeded 260mm, so it was not necessary to use supports. Fig. 8 shows how the prototype vent elements are arranged in the program representing the printer's workspace.

Using the possibilities of 3D printing, it was also decided to design a new roof vent (Fig. 9). The assumption was to abandon the steel structure in favor of plastic. This means that there is no need to adapt the new shape to the limitations of metal-working technology and the welding process. This allowed for the development of an innovative shape, the implementation of which would be impossible as a steel structure.

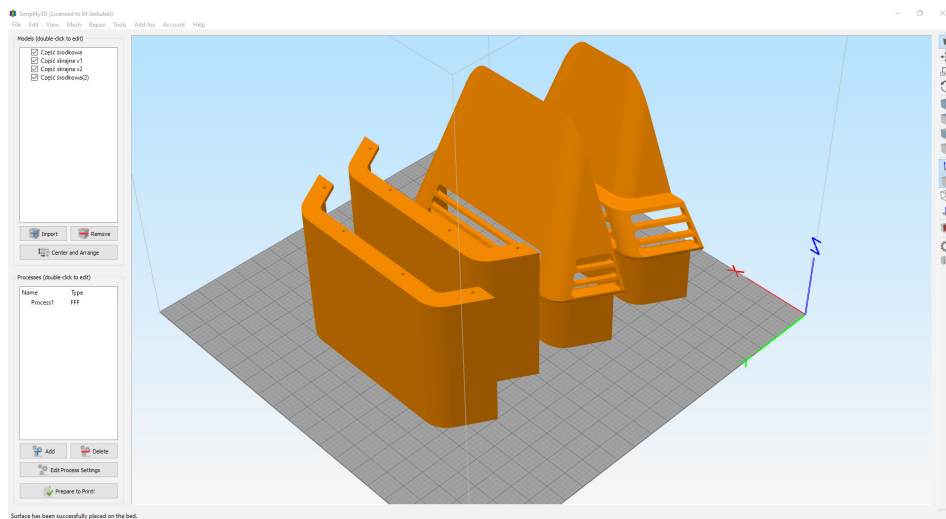


Fig. 8. Program window with the arrangement of the vent components

Source: Own study

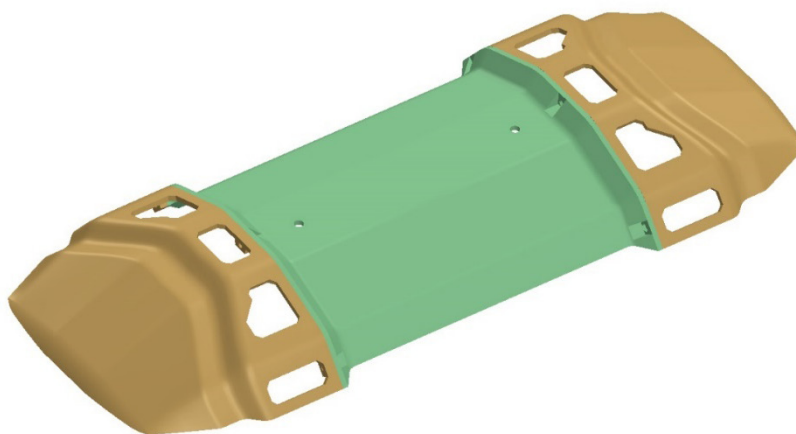


Fig. 9. The concept of a new vent

Source: Own study

Fig. 10 shows the arrangement of the new vent elements in the machining program.

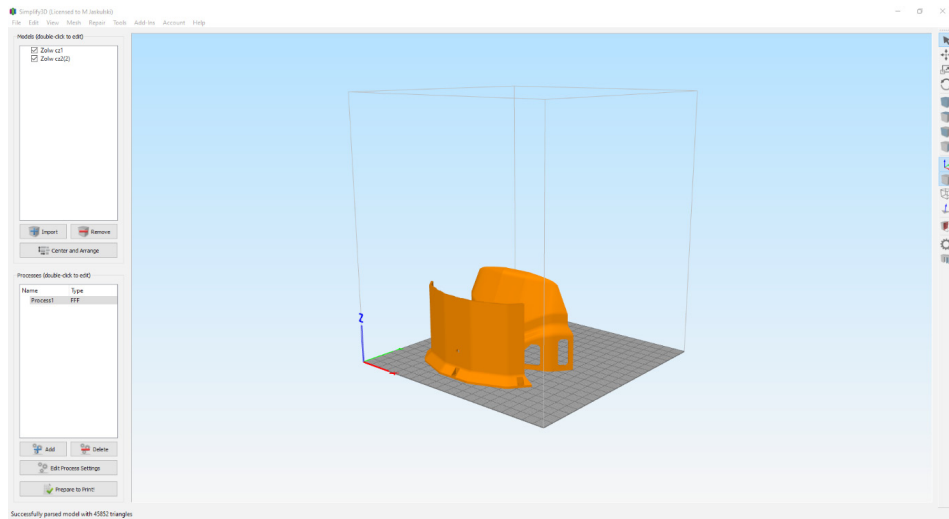


Fig. 10. Arrangement of the components of the new vent in the machining program

Source: Own study

The data prepared in this way was converted into an STL file, which was sent to the printing device.

Prototyping

Nylon material with the addition of carbon fiber was used to make the prototype. After printing, the finished model (Fig. 11) had to be thoroughly cleaned with compressed air and the quality verified in terms of dimensional consistency and possible defects such as material delamination, shifts of individual layers in relation to the others, which could weaken its structure.



Fig. 11. Finished vent print
Source: Own study

The printed model was installed on the roof of 10 wagons and tests were carried out on the test station for checking the tightness of the wagons. Water is sprayed from specially arranged nozzles onto the roof and side walls of the wagon. The search for possible leaks is performed visually by production employees. In this case, no leaks were noticed inside the vehicle, so the vent successfully passed the tests, which confirmed the original assumptions. The tests were conducted in two stages: in the first stage, static tests were carried out and in the second stage, dynamic tests were made. Static tests were conducted on a special test stand shown in Fig. 12. The tightness test is conducted by spraying the vehicle roof with a stream of water at a pressure of 0.5 atm. , at an angle of 0 - 60 degrees. The time of such a static test is 15 minutes. Dynamic tests were conducted during a test run of the wagon on the Poznan - Rawicz - Poznan route (total distance 200 km). Dynamic tests allowed to check the correct operation of the entire ventilation system in real conditions.

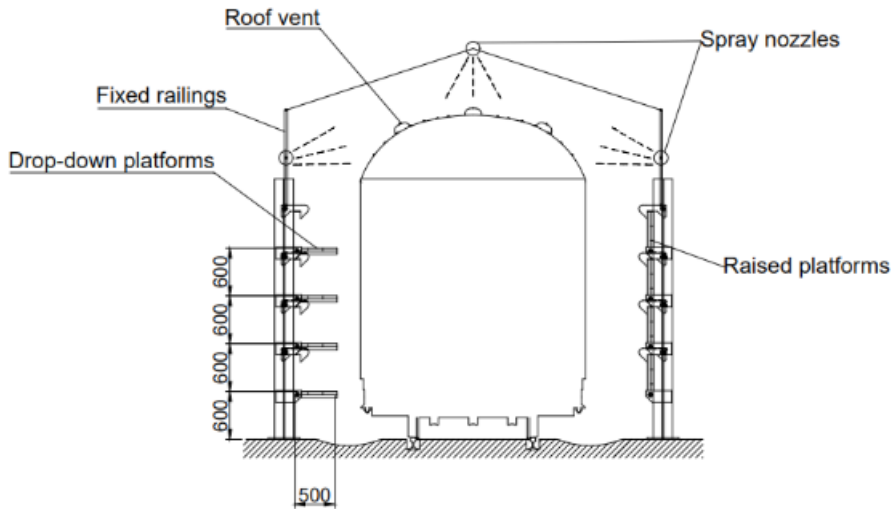


Fig. 12. Static tightness test stand

Source: Own study

After passing all the tests and confirming it's functionality, further work is based on the introduction of appropriate modifications to the original element if necessary and the development of construction documentation.

Possibility of installation of 3D printed elements in rail vehicles

The use of plastic materials in all types of rail vehicles is regulated by the PN-EN 45545 standard for their fire protection. Unfortunately, this significantly limits the choice of materials from which plastic elements can be made. This also applies to materials intended for 3D printing. The research shows that printing of the polymer causes thermal stress to the molecules which may lead to a worsening of the flammability. The additives and the print density both affect the flammability properties depending on the polymer type (Hohenwarter et al., 2020, pp. 99-107). In a result properly selected print parameters and additives can reduce flammability of 3D printing polymers which is a good news for railway industry. Due to this fact, materials with flame retardant additives that meet the requirements of the PN-EN 45545 standard have recently appeared on the market. This allowed the use of elements made of these materials in various areas of the interior of the wagons.

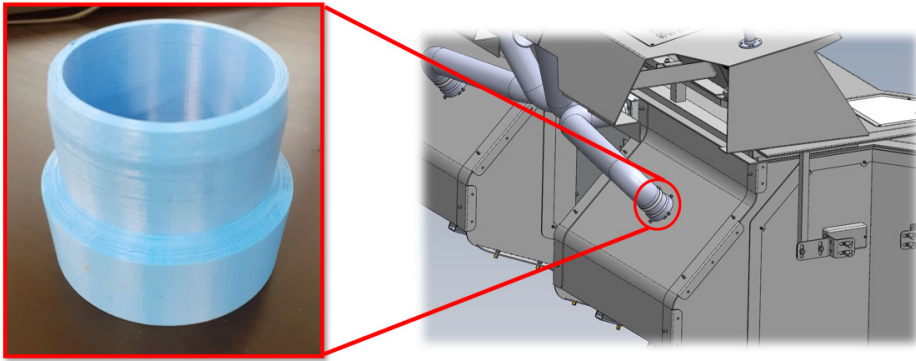


Fig. 13. Reduction of the air supply system
Source: Own study

An example of another application may be a reduction (Fig. 13) in the air duct of the multiple traction unit driver's console. Based on technological analyses, obtaining this element thanks to 3D printing technology allowed for a significant acceleration of assembly work and minimization of production costs.

Conclusions

There are many methods which include in the RP technology, but thanks to the universal purpose of 3D printing, it is the one of the most often used in prototyping rail vehicle parts. This technology is an additional tool in the designer's work, supporting the design process by refining the concept of the product before its serial production begins. Thanks to the RP technology, a prototype of a roof vent was designed and manufactured, the quality tests of which were carried out on a test stand for testing the tightness of wagons. Results did not show any visible leaks inside the vehicle, which confirmed compliance with the original assumptions. The considerations carried out, based on analyses of technological routes, confirm the adopted thesis, that the RP rapid prototyping technology accelerates and facilitates work related to the design of components of civil and military rail vehicles. However, it should be borne in mind that designing for 3D printing differs from standard design, e.g. steel structures. Additional aspects that result from the limitations of this technology should be taken into account, such as: printing very thin walls, the size of the element related to the working space of the machine, the need to use supports in complex details. Thanks to the rapid development of this technology, this is also accompanied by an increasing selection of materials for 3D printing, including materials that meet the requirements of the PN-EN 45545 fire

protection standard. This allows such elements to be used in the construction of rail vehicles. The accuracy of this technology also allows it to be used for the production of fitted parts as well as for the production of mechanisms such as hinges, latches, etc. Undoubtedly, however, this technology in relation to the production of rail vehicles requires further development, primarily towards enabling mass production of components, as well as the production of large-size elements.

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