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LCA comparing 3D printed splints to conventional splints for traumatic injuries

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Abstract

In the context of climate change, hospitals that use significant amounts of disposable products are undertaking sustainability initiatives. This can be supported by Life Cycle Analysis (LCA), in which an increase is noted in the medical domain to study and implement sustainable alternatives. However, the sustainable implementation of new technology such as 3D printing to generate personalized medical devices raises additional challenges. As common wrist injuries like a distal radius fracture, show a high prevalence (200-400 times per 100.000 persons), the department of trauma surgery at the Radboud University Medical Centre in Nijmegen, is focusing on implementing 3D printing of personalized splints. Simultaneously, a case study is initiated to assess the environmental impact of this innovation with conventional medical devices: mineral or plastic splints. This research enhances future work on sustainability implementation of the 3D printed splint treatment for wrist injuries, potentially expediting its adoption as the standard treatment. This project raises awareness about the environmental impact of medical products and treatments, while fostering collaboration for future sustainable projects in the hospital.

Keywords: LCA; Case Study; Medical Treatment; Sustainable Manufacturing; Healthcare Industry; Knowledge Transfer; Additive manufacturing

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1. Introduction

Hospitals can produce up to 3.23 kg/bed/day of waste, of which not even a quarter is waste with infection danger [1]. Recycling of medical waste could be possible, but there are some challenges: the legal obligation of medical device manufactures to use virgin materials in production, financial dependency on the single-use business model, the ease and sterility of single-use products and a non-optimized infrastructure for sorting medical waste [2, 3]. Attitudes toward recycling medical products are shifting positively with the growing awareness to promote healthy living. Initiatives are being taken to change attitude regarding sustainability [4]. This is not a straightforward task due to lack of insight, lack of time or lack of clarity where to begin [5].

Life Cycle Assessment (LCA) can support gaining insights in environmental impact of healthcare procedures and medical devices. It pinpoints processes and products with a high environmental impact, called hotspots. Identifying these hotspots create insight on what products should be the focus for sustainable improvements. Two categories of LCAs are common in the medical field. First, studies that compare reusable and disposal products [7, 8, 9]. These studies prove that the reusable alternative medical devices have a lower environmental impact than the disposables. Careful interpretation of these results is necessary as they depend on temporal and geographical aspects and show sensitivity to underlying assumptions. Second, LCA studies that investigate different techniques of a particular medical procedure [10, 11, 12]. These studies aim to decrease impact by providing insights

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into the environmental impact of various aspects of the different medical techniques and highlight the hotspots.

The Radboudumc, a level 1 trauma and university medical center in Nijmegen, the Netherlands, is a precursor to other hospitals in the Netherlands regarding the implementation of sustainability [12]. One of the LCA projects focusses on the conventional treatment of injuries of the extremities with medical devices class I [13]. In particular, it focuses on the conventional treatment of distal radius fractures. Typically, medical devices, such as a mineral or plastic splint, are used to immobilise the limb. An alternative method was developed within Radboudumc that enables the 3D design and printing of personalised splints (3Dx splints). Besides the potential to improve comfort of wear for the patient and logistical aspects of the treatment, the use of 3Dx splints might decrease the environmental impact of treatment of injuries of the extremities in military and civilian context.

This paper focuses on a comparative LCA between these three medical devices. This would result in identifying hotspots to reduce the environmental impact of 3Dx splints.

2. Method

An inventory of all products necessary for the treatment with three different splints was conducted. Using this inventory data, LCA models were made of the three splints and their accessories according to ISO 14040 and ISO 14044 [16, 17] using the modelling software GaBi [16]. The impacts were determined by using the ReCiPe 2016 method [17]. The hotspots were interpreted following the guideline of the European Committee [18]. Additionally, the robustness of the GaBi model was assessed with a sensitivity analysis on the five most impactful materials and their manufacturing processes.

2.1. Goal & scope phase

The goal of the LCA is to assess the environmental impact of the two conventional splints and the 3Dx splint, and to highlight opportunities for improvement in terms of sustainability. This study was used to inform people of interest in the hospital and the people involved in the 3Dx splint project, as well as other hospitals interested in environmental impact of splint treatments.

This LCA was carried out based on the standardised medical workflow for fracture treatment within Radboudumc. This treatment of distal radial fractures is similar for hospitals in the Netherlands, European countries as well as other developed countries. The used medical devices can be slightly different or purchased from another manufacturer or distributor. However, it is expected that they are made of similar materials with similar manufacturing processes. Hence, the conclusions from this LCA study can be deemed valid for hospitals in the Netherlands and most of Europe.

To address temporal validity, it is important to note that the 3Dx splint is being implemented in several phases due to continuous development of design and manufacturing techniques. Eventually, the objective is to offer only the 3Dx splint as a substitution for the conventional splints. Therefore, some processes in this study will evolve, while others have been in use for decades and are likely to remain so for the next 10 years.

The scope of the LCA encompasses the entire life cycle of the splint products, starting from raw material acquisition and manufacturing, through packaging, transportation, use, and ultimately the disposal of the products. These products consist of the medical devices and the products necessary to execute the treatment (medical accessory products).

The functional unit that is modelled is:

'Immobilize the wrist of 100 patients with a distal radius fracture'.

The LCA is limited to fracture treatment involving only the application of the splint itself. Diagnosis, anamnesis, transportation of patients and climate control in the rooms are outside the scope of this study. Furthermore, the life cycle is included of all products, materials, energy, and water inputs directly involved in application of the splint in all stages, scope 1&2.

To ensure data quality, inventory data of the actual products used during the splint application was collected through observations, followed by noting the brand and type of products and by performing interviews with medical professionals to confirm usability. In the case of the 3Dx splint, the pilot study was observed [19]. Product data about production, use and disposal came from medical and waste management experts in the hospital and datasheets of the manufacturers. When specific datasheets were unavailable, a datasheet sufficed of a comparable product from a different manufacturer. As a last resort, estimations by LCA experts were used. To ensure quality of these assumptions, a sensitivity analysis was performed for those that were most impactful.

When specific materials or processes were not available in the GaBi database, reference materials and processes were selected by investigating materials and processes with similar CO2 footprints and embodied energy using Granta EduPack 2022 [20].

2.2. Inventory analysis

This study focuses on the conventional treatment of the distal radius fracture, because it is the most common type of fracture (Fig. 1 [21]). It involves immobilisation of the affected limb by providing a splint. If treatment mandates a longer duration of immobilisation than one week, the splint is replaced with another after the swelling has subsided. The duration of

Fig. 1. Posteroanterior and lateral of a DRF, fracture is located by arrow[21].

the splint immobilisation is dichotomous: short immobilisation of one week with one splint for nonreduced fractures (one third of cases) and long immobilisation with two splints for reduced fractures (two thirds of cases). The three types of splints can be applied in both the short and long immobilisation.

Patients will generally come to the hospital twice in case of a short immobilisation period and thrice for the long immobilisation period. Typically, the first visit is at the emergency department where the diagnosis is made and the splint is applied. Follow up is at the outpatient department for either a change or ultimately removal of a splint. Additional visits are planned in the eventuality of a patient experiencing pain due to pressure of the splint or when the splint itself has become damaged. This involves application of a new splint. For the short immobilisation of all three splints, the splint and medical accessory products are only used once. For the long immobilisation of all three splints, the splint products and medical accessory products are required at least twice. For the analysis in this paper, the use of one splint is investigated.

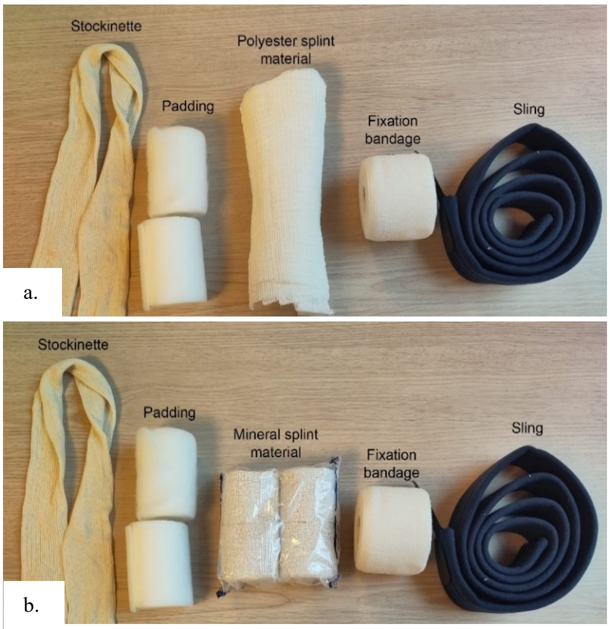

Fig. 2. (a) Plastic splint products; (b) mineral splint products.

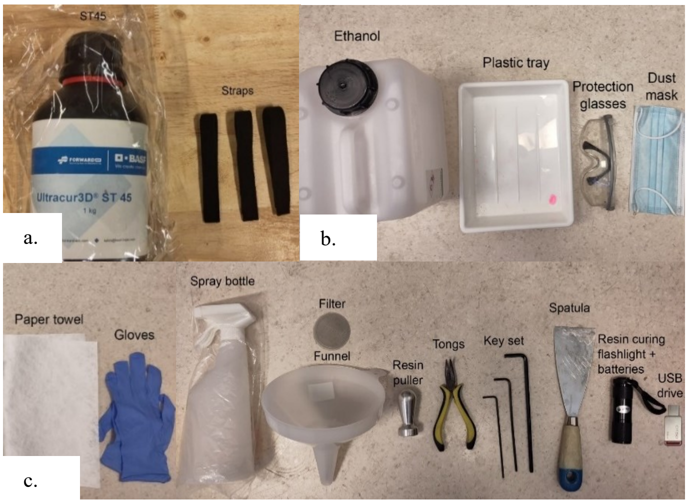

Fig. 3. (a) 3Dx splint products; (b, c) 3D print accessory products.

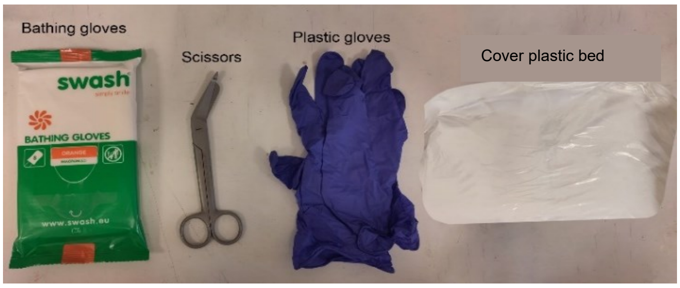

Fig. 4. Medical accessory products.

Fig. 5. 3Dx splint after application [19].

The conventional treatment can be executed using either the mineral splint (gypsum-based material) or the plastic splint (polyester-based material).

Immobilisation by splint consist of combining several products. These are the stockinette, padding, fixation bandage and splint material itself for the conventional splints (Fig. 2) and 3D print resin and straps for the 3Dx splint (Fig. 3). Medical accessory products are products that are necessary to apply the splint, including plastic bed cover, gloves and bathing gloves for cleaning the patients skin (Fig. 4).

3D print accessory products to make the 3D printed splint include for example ethanol, tongs and protection glasses (Fig. 3). It is important to note that in contrast with all other products, the 3D print accessory products can be reused until they do not fulfil their function anymore. These include all 3D print accessories except the paper towels, gloves, dust mask and ethanol. Therefore, the immobilisation using two or more splints does not require multiple times the amount of 3D accessory products. The final 3Dx splint after application is visible in Fig 5.

Data on waste disposal was collected by interviews with medical professionals and hospital waste management.

All production processes and materials were modelled using the GaBi database 2021.2. Not all necessary manufacturing and packaging information was disclosed by the manufacturers, instead existing, similar, manufacturing processes present in the GaBi database were used. The most important assumptions that were made are listed below.

- Disposal is modelled as 70% recycling of cardboard and waste incineration for rest waste.
- Transport is simplified to transport of raw materials, transport to distribution centre, transport to hospital and disposal transport.
- The cover plastic can be simplified to the use of one cover plastic, for both application and removal, since the cover plastic is not replaced with every patient.
- The reusable 3D print accessories of the 3Dx splint treatment are reused 100x.
- The production of the 3D print resin (ST45) has a similar environmental impact as the production of epoxy resin.
- The production of gypsum-based material has a similar environmental impact as the production of a gypsum interior panel.
- The production of the straps and Velcro is similar to the knitted fabric manufacturing of cotton.

2.3. Impact assessment

To determine the effects of processes and materials on the environment, ReCiPe 2016 was used. This method describes 18 midpoints, which are aspects that effect the environment.

To draw conclusions on the overall environmental impact of the splints, a selection was made of the three midpoints that had highest impact (fossil depletion, human toxicity cancer and climate change). The midpoints were evaluated by a panel of healthcare students and these three were deemed most relevant. To ensure quality of the results, other midpoint impacts were analysed, but did not change the conclusions and confirmed the most important factors of impact as presented.

Fossil depletion is the reduction of available fossil fuels. Besides as fuel, they are also used in material production for plastics [22]. Human toxicity cancer concerns chemicals that specifically can lead to cancer in humans. The intake of these chemicals can be via air, food/water and penetration through skin. [23]. Climate change concerns effects of the emissions of various greenhouse gasses. The emission of greenhouse gases lead to an increase in the global mean temperature, effecting human health and ecosystems [24].

2.4. Evaluation

To ensure robustness of the GaBi model, a sensitivity analysis was done with five materials by feeding alternative materials and manufacturing process into the model and comparing these results to the reference results using weighted midpoints of ReCiPe 2016 and the following formula:

$$Sensitivity\ [\%] = \left| \frac{Impact\ alternative - Impact\ reference}{Impact\ reference} \right| \times 100 \qquad (1)$$

Apart from the top four materials that showed highest impact, gypsum was also selected, since it was the only material difference between the plastic splint and the mineral splint. Furthermore, polyacrylonitrile was a high impact material, but its sensitivity could not be checked. As stated by EN15804, updates of the model are required when results change +/- 10% [22]. The results of the model are therefore deemed valid when sensitivity of the materials stays under 10% (see 3.2.).

3. Results

3.1. Results LCA

The LCA results are shown for: climate change, human toxicity cancer and fossil depletion (Fig. 6). The 3Dx splint has the lowest impact compared to the mineral and plastic splints. Furthermore, the midpoint human toxicity shows highest value for the mineral splint, whereas for the other two midpoints, the plastic splint shows highest values. On the midpoint human toxicity, the difference between the 3Dx splint and the conventional splints is the highest.

Fig. 7 shows the impacts for all splints per life cycle phase (production, use, disposal and transport). For all three splints the production is dominant (>60% of total impact). The lowest impact is the use phase for the mineral and plastic splint, which is barely visible (<0.0001%).

The materials and products with the most environmental impact are analysed for all three splints. When a product contributed to 5% or more of the total impact of a splint on a midpoint, it is considered a hotspot [18]. It was found that the three midpoints showed the same trends in high impact materials. Therefore, only the graph of climate change is visualised in Fig 8. The mineral and plastic splint have the same materials as high impact hotspots, for example cotton, low density polyethylene and polyacrylonitrile. For the 3Dx splint, other materials are used in the production and therefore, 3D

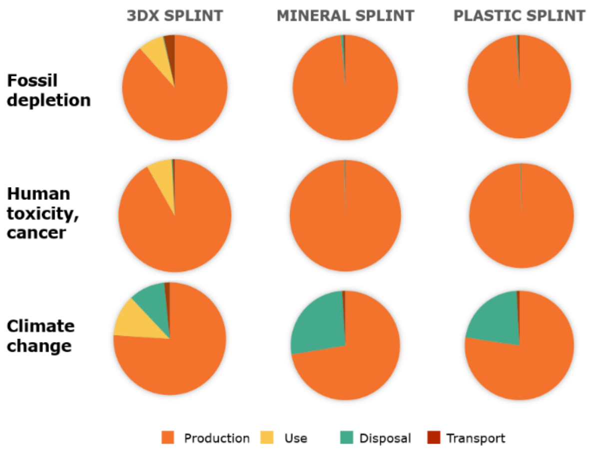

Fig. 7. Environmental impact of life cycle phases of the three types of splints on three midpoints of ReCiPe 2016.

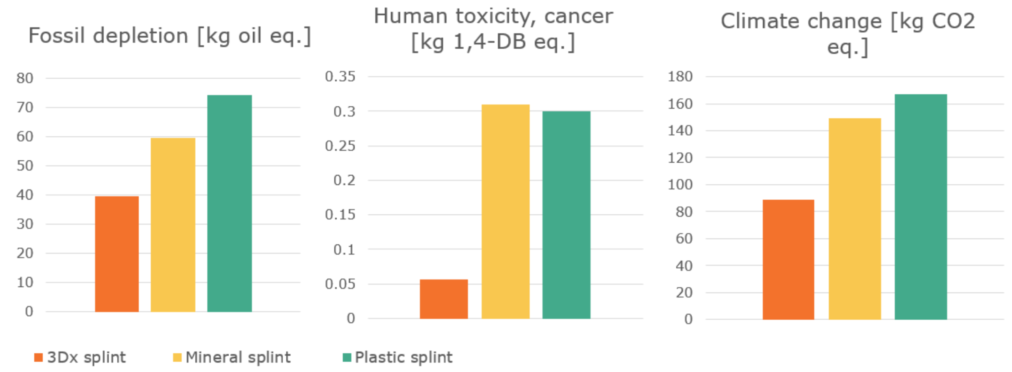

Fig. 6. Environmental impact of the three splint types on three midpoints of ReCiPe 2016.

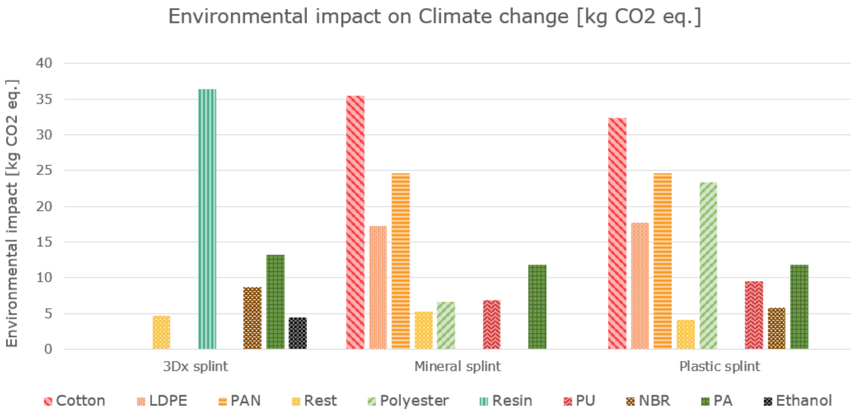

Fig. 8. Environmental impact of various materials in the three splint types on midpoint Climate Change of ReCiPe 2016.

print resin, nitrile butadiene rubber and polyamide are high impact materials.

3.2. Results sensitivity analysis

The sensitivity is calculated of the five materials with the highest impact (Table 1). Those materials include polyester, cotton, low density polyethylene, 3D print resin and gypsum.

All materials and processes remain below the threshold level of 10%. Therefore, the initial model shows sufficient robustness for the results of the LCA.

Table 1: Results sensitivity analysis

Reference material/process	Sensitivity (%)
Polyester	3.86%
Cotton fibres + textile manufacturing – woven fabric	9.51%
Polyethylene low density + blow moulding	0.514%
Mineral material	0.290%
Resin	5.23%

4. Discussion

Environmental impact of the 3Dx splint is lower than the impact of conventional splints (Fig. 6). For all splints, the production phase shows dominant impact (Fig. 7). Therefore, a detailed analysis of the materials was performed. The mineral and plastic splints show similar values for the three midpoints, except for the material polyester which gives a higher impact for the plastic splint. The 3Dx splint is produced from different materials (Fig. 8) with the 3D print resin showing highest impact. However, its impact is still lower than the impact of the components of the mineral or plastic splint (Fig. 8).

From the in-depth analysis of the materials, the hotspots are found that offer room for environmental reduction. Implementation of the 3Dx splint, without the use of a temporary conventional splint, can accelerate environmental reduction. Other possibilities to reduce environmental impact are applying bio-based materials and/or recycling and/or reuse. This will be investigated in a follow up study.

As mentioned in 2.2., the treatment of a distal radius fracture can be performed using a short immobilisation or long immobilisation. However, not all materials are used twice when using two splints, meaning that long immobilisation does not result in exactly two times the environmental impact of the short immobilisation.

The results are of relevance as the prevalence of traumatic injuries at the level of the wrist was 50621 in 2022 in the Netherlands[25]. Of those, a total of 55089 mineral and / or plastic splints were applied. These numbers include conservatively and surgically treated injuries in general and distal radius fractures specifically. Potentially, almost all these cases are suitable for a 3D splint. With the indicated number of distal radial fractures, the presented results would contribute to a decrease up to 43.000 kg CO2 equivalent in environmental impact on the climate change midpoint. Using the methodology as presented for the 3D splint for distal radial fractures can be relatively easily applied to similar cases for other types of fractures that require immobilization with a medical device.

4.1. Limitations

The level of detail in the models might not be entirely equal to simulate the three splints and their medical accessory products. All accessories for the 3Dx splint are included. Some of them are rarely used, like the key set, resin curing flashlight or filter and funnel. Including all accessories presents a worst-case scenario for the 3Dx splint, while no worst-case scenarios are presented for the conventional splints. This supports the conclusion that the 3Dx splint would be the more environmentally friendly alternative.

Assumptions were verified with the sensitivity analysis (Table 1). However, for transport, the process was simplified to four steps, while it could be more. It is expected that adding additional transport steps will not change the overall conclusions because the phase itself is quite small.

The assumptions for reference materials were based on equivalency of CO2 footprint. It is expected that the impact of the actual materials is a bit lower than the reference materials, but it will not change the overall conclusions. The influence of the production of plastic materials was minimal, while textile manufacturing-related processes had a high impact compared to other production processes. The accuracy of the textile manufacturing processes depends on detailed information.

The results of this LCA study were analysed using ReCiPe 2016 midpoints and focused on three midpoints that were found most impactful. In a non-disclosed research report, a thorough assessment including all eighteen midpoints was considered and weighted intro an indicator.

4.2. Recommendations

It is recommended to present the results to the medical professionals executing the treatment. These insights might accelerate the transition to a more environmental conscious treatment development.

Furthermore, it should be considered to implement the 3Dx splint in civilian and military setting without an initial conventional splint. Various materials could be investigated to determine the most sustainable material for the 3Dx splint and reduce environmental impact even more. This is also recommended for the type of 3D printer. Possibly, other 3D printers or new updates show prints with the same accuracy and speed but using less energy.

Conclusion

This comparative LCA study illustrates that the 3Dx splint is the more sustainable friendly option and that hotspots were mostly found in the conventional splint materials. Implementation of the 3Dx splint treatment would beneficially affect the environmental impact of a splint treatment.

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