Rapid Prototyping in Humanitarian Aid To Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan

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Abstract
This research examines the use of rapid prototyping technologies in the supply chain of spare parts. Spare parts are manufactured in small production lots and distributed in wide areas, eventually requiring short delivery times. The focus of this research is the use of rapid prototyping in humanitarian logistics. The demand of humanitarian aid is large, but it is very difficult to predict and also to supply. The use of rapid prototyping to produce spare parts can greatly increase the availability of scarce resources. In this paper, it is demonstrated that rapid prototyping of spare parts for last mile vehicles can help achieve a cost-effective solution to increase vehicle availability. Also, a detailed implementation plan is developed to serve as a guideline for any organization to successfully introduce the equipment in their operations. © 2016 Wiley Periodicals, Inc.

Keywords: Humanitarian aid; Rapid prototyping; Supply chain; Spare parts; Reverse engineering

1. INTRODUCTION
Billions of people have been in need of humanitarian aid during the last decade because of more than 35 major conflicts and 2,500 disasters, and the impact of disasters is expected to increase 25% because of global warming and pandemics (Van Wassenhove & Pedraza Martinez, 2012). An agile supply chain is needed to provide humanitarian aid in the shortest time possible.

The humanitarian aid supply is radically different from other supply chains. The demand is by definition decentralized with multiple parties involved and very limited resources. At the moment, there is a big gap in logistic performance between commercial and humanitarian operations. As stated by Van Wassenhove (2006), humanitarian operations are 15 years behind the private sector. Even though there is a significant difference in the purpose and conditions of the supply chain, commercial logistic approaches can be adapted to reduce lead times and improve productivity of the humanitarian logistic operations.

The use of rapid manufacturing technologies is spreading in the industry because of its many advantages. Rapid prototyping can be used to produce parts on site to avoid transportation time and costs. The biggest benefit is in development time and cost: rapid prototyping can reduce the development time by 50–60% (Lopez & Wright, 2002) and the development cost (mainly due to the cost-efficient production of prototypes) between 30% and 60% (Shan, Yan, Zhang, Lu, & Guan, 2003). This technology shows also great promise in humanitarian aid. In this paper, production of spare parts on an emergency site using rapid prototyping (RP) is analyzed.

2. HUMANITARIAN AID SUPPLY CHAIN
Humanitarian aid is quite different to industry or military supply chain. On one hand, humanitarian aid may be needed in unsecure areas where transportation networks are nonexistent or, if they exist, may become chaotic. While military in these situations is clearly compartmentalized and have a clear control structure,
humanitarian aid involves very different players wherein volunteer or temporal staff may not have the training necessary. Lack of information is sometimes a symptom of this disorganization; that is, in the earthquake in Haiti, many international humanitarian organizations (IHO) could not confirm how much of the prepositioned inventory had survived (Van Wassenhove & Pedraza Martinez, 2012). Also, there is another unique issue that makes humanitarian supply chains radically different from commercial or military supply chain: the uncertainty of supply. Available resources depend on the donation process, and it is very difficult to know the available budget beforehand.

Vehicle fleet management is one of the key points to a successful humanitarian operation. Vehicle availability can become a bottleneck in logistics because vehicles are used to transport staff, material, or other resources to the place in need. After human resources, transportation is the second largest cost for humanitarian organizations (Disparte, 2007). If any vehicle needs repairing, the unavailability of vehicles may cause a severe delay in aid reception in a very time-sensitive situation. The distribution of the aid to the population in need is often referred as “last mile distribution” (Balci, Beamon, & Smilowitz, 2008), and the 4 × 4 vehicles used for these tasks are known as last mile vehicles (LMV) (Stapleton, Pedraza Martinez, & Van Wassenhove, 2009).

The long distances covered and the inadequate fuels, combined with the harsh ambient conditions and the severe solicitation, make LMV maintenance and repairs more common than in most applications. In addition, there are very few workshops on site, so in most cases drivers with little mechanical skills may be required to do maintenance tasks. In the event of repairing needed, the spare parts may take a significant amount of time because transport infrastructures are already operating at full capacity.

Hajdarovic and Jensen (2014) interviews are conducted to evaluate the fleet management activities of IHO. Maintenance is described as a big bottleneck, very country specific, making it difficult to have a standard approach. No authorized dealers make using the inadequate local workshops the only solution apart from having their own facilities (Martinez, Stapleton, & Van Wassenhove, 2011). Between the proposed solutions, one stands out: the deployment of mobile workshops.

Still spare part supply is a challenge of its own: insufficient funds and planning are added to the transportation and repairing problems. Some IHOs secure the spare parts by shipping a comprehensive set with each new vehicle; enough to service their life duration. This is a solution for isolated areas where humanitarian aid is permanently deployed, but it is not possible to manage for punctual aid transportation, such as disaster sites.

As indicated by Hajdarovic and Jensen (2014), Toyota Land Cruisers are the preferred choice for LMV because they have little electronics and straightforward repairs. A growing concern is that vehicles are becoming more complex, and local workshops and even IHO mechanical staff do not have the know-how to keep up with the complexity of new vehicles. Additional support from the manufacturer is needed to ensure the shortest repairing time.

To ensure that spare parts are up to date with the vehicle manufacturer requirements and that the repairing time is minimum, only two options are available: 1) ship a complete set of spare parts or 2) manufacture these parts in situ. The first option is not desirable when an emergency arises because early delivery of other goods (to cover basic needs for the victims) is a priority. To produce spare parts locally is a better choice, and in this task, rapid prototyping technologies is a preferable manufacturing method because of its flexibility. This core decision is also present in commercial supply chains, as shown in the next section.

3. COMMERCIAL LOGISTIC APPROACH TO THE SPARE PART SUPPLY CHAIN

Rapid manufacturing is presented as an interesting alternative to traditional production methods in manufacturing spare parts, because of the flexibility of the RP technologies and their potential use in reducing manufacturing time and supply chain management. That said, the supply of spare parts must meet a set of characteristics, and it must provide the necessary units, maintaining the customer satisfaction at an acceptable level but also looking to reduce operating costs (Andersson & Marklund, 2000).

To increase the time a machine or device is operational, it is essential to stock spare parts to replace units as quickly as possible in case of failure. In case of highly complex machinery, when time to repair is minimal, it is necessary to have available a number of all the parts that can be damaged. This entails a very high cost and is not always technically possible. Another option is
to manufacture in situ the necessary parts for maintenance. Choosing between these options, it is necessary to study which one solves more efficiently the following difficulties in the supply chain.

The first problem that can be found in a supply chain of spare parts is to combine the production of the spare parts with the manufacture of new products. This can be solved in two ways (Khajavi, Partanen, & Holmström 2014). The first option is to produce a lot of parts in one run, and planning the next lot in a long time interval. This results in lower costs and lower production line stops but higher storage costs. The other possibility is to manufacture on demand, resulting in higher production costs for the continued disruption of production tasks, and the possibility of producing a lower-quality product because operators are not used to these tasks, and there is no possible interval for learning.

The second problem is the difficulty of predicting the demand, especially in new product launches because the failure rate of parts is not available (Simao & Powell, 2009). The instability of demand can cause additional spending on storage of nonresponder units or a delay in delivery of the spare parts (which affects customer satisfaction). These two challenges make it difficult to provide a high-quality service at low cost with regard to spare parts (Khajavi et al., 2014).

Another point to take into account is the end localization of the spare parts. Depending on the transportation involved in the operation, there could be an incentive to avoid transportation altogether. This is the case of isolated locations. A system is considered logistically isolated when external conditions govern the supply operations (Grenouilleau, Housseini, & Péres, 2000). Supply problems may be due to equipment (spare parts, tools, documentation) or manpower (clothes, food, protection). This is a particular case in which the rapid manufacturing technologies can be useful.

There are two different types of isolation: permanent or temporary (Péres & Noyes, 2006). If the insulation is final, it may be due to lack of communication (polar regions, mountains, forests), the nature of the environment (air, water, space), and potential risks of location (battlefields, epidemics, natural disasters). If the isolation is temporary, it refers to a limited time, that is, the closure of production lines, when production has been significantly greater than demand, while current market supply can be met with storage units.

The conditions of manufacturing aid—the difficult prediction of demand, the supply uncertainty, and the remote locations in which the operations take place—makes in situ manufacturing of spare parts the preferable choice also from the commercial point of view.

4. RAPID PROTOTYPING TECHNOLOGIES ADVANTAGES

RP is a process of creating a model from a file generated by computer-aided design (CAD) software. The different technologies used to create prototypes can be sorted whether they add, shape, or remove material (Chua, Leong, & Lim, 2010). Most RP processes fall under the first category. These processes, when used to manufacture a final part, are known as rapid manufacturing (RM) processes (Kruth, Leu, & Nakagawa, 1998).

The benefits of RM technologies over conventional manufacturing methods are highlighted in (Holmström, Partanen, Tuomi, & Walter, 2010):

- Not necessary tooling (economy of scale does not exist, which enables customization and continuous review of designs)
- Ability to produce small production lots with reduced cost
- Ability to quickly design modification
- Optimization of the product due to functionality
- Economic production of customized products (lots of one part)
- Ability to produce complex geometries
- Potential for supplying with shorter lead times and smaller inventories

RP technologies can be used to manufacture different part geometries with a short production time. In many cases, the same equipment can produce parts of different materials. The operation of the equipment needs little supervision; once the file is loaded, the machine can operate autonomously (Péres & Noyes, 2006). In addition, the equipment is quite compact and can be transported with relative ease.

The high degree of automation of rapid prototyping technologies makes it suitable for flexible manufacturing. Since 1997, it has been possible to obtain parts manufactured by RP in 24 hr. One of the first companies to offer this service is the Belgian RP service bureau (Kruth et al., 1998). The short lead
time is possible because of an efficient computer data management and process automation.

5. LAST MILE VEHICLE SPARE PART MANUFACTURING

There are several case studies that show the spread of RP technology (Chua et al., 2010; Holmström et al., 2010; Kamrani & Nasr, 2006; Liou, 2007; Onuh & Yusuf, 1999), and humanitarian aid operation can also benefit from its advantages. Tatham, Loy, and Peretti (2014) proposed a manufacturing method suited to produce basic goods, as it avoids transporting goods “just in case,” and production is adapted to the demand. It can also be used to produce medical equipment and tailored prosthetics to help in medical campaigns. All these applications justify the investment and transportation of an RP machine to an emergency site. The production of spare parts adds up to them.

RM in the production of spare parts is rapidly increasing in the industry. Above all, this is mainly used in applications that have short batches, numerous versions, customization, or continuous technological improvements. Rapid prototyping technologies have greater flexibility than traditional production techniques and are presented as an alternative to them when the product is constantly changing.

In this paper, two different approaches of in situ spare part manufacture are discussed. With both of them, the repairing time and cost can be greatly optimized as shown in Figure 1. The first case is the current situation: a problem is diagnosed by the mechanics on site, a spare part is requested to the manufacturer, the spare part is shipped and later on received, and the damaged part is changed. The second case shows the improved situations taking into account manufacturer cooperation: the diagnosis and detailed explanation of the problem is sent to the manufacturer, the manufacturer proposes a solution and provides the three-dimensional (3D) model to manufacture any part to replace, the spare part is produced locally by RP, and finally the part is changed, and the vehicle is available again. The third case considers that the manufacturer does not contribute in the process; therefore, the 3D model is not available. To obtain the 3D model, the damaged part is scanned using reverse engineering (RE) methods.

Repairing time is improved and, consequently, vehicle availability because transportation of the spare part is not required. This eliminates the need to transport through international borders, reducing the chance of further delays due to paperwork or customs and eliminates stealing/losing risks. Costs may also be improved because vehicle unavailability costs are likely severely higher than the increment of part production cost with rapid prototyping.

The greatest benefit in logistics for using RP technologies is the reduction of repairing time. One example is presented by Pères and Durand (2002) in which the number of days to maintain a subsystem of a space station with traditional supply methods is compared to in situ manufacturing. The maintainability improved in the second case from 53.5 days to 140 days in the worst case. This is a reduction of logistics lead time of more than 60%.

Moreover, a relationship between the use of RM technologies and the human resources assigned to a mission is observed. With a data connection and a camera, most of the functions (file preparation, equipment calibration, verification of production) can be performed remotely, except cleaning and finishing tasks (Pères & Noyes, 2006). It is not necessary to relocate qualified technicians because the specialized workload can be performed from the headquarters.

Although the use of RP technology has many benefits, it also has limitations, and a full assessment is

![Figure 1](https://via.placeholder.com/150)

**Figure 1** Approaches to spare part supply chain.
needed before considering its use. It needs to be considered that not every part can be manufactured with this method. The materials most commonly used in RM technologies are polymers, paper, and ceramic composites, but because of the complexity of the process and especially the cost, manufactured metal parts are scarce.

Also, considering the use of RP does not resolve the difficulties in the maintenance processes. If industry can be reached, there could be room for a mutual agreement in which manufacturers have information about vehicle operation in harsh conditions and in which IHO can have the manufacturer support to discover the root cause of the vehicle malfunction faster. Also, if the CAD file is provided damaged parts can be manufactures in a shorter amount of time. An agreement between manufacturer and IHO is clearly beneficial for both sides.

If the manufacturer cannot be reached, in addition to the RM equipment, an IHO will also need trained staff to diagnose the faulty part on a damaged vehicle and RE equipment to reconstruct the CAD file from the damaged part. This will require more time than in the previous option, but it will reduce the amount of time the vehicle is unavailable compared with the current approach.

6. IMPLEMENTATION PLAN

To clarify the points in applying this technology and to help in deciding the IHO that will explore the possibility of using RP equipment, all the required steps are summarized to deploy spare part manufacturing equipment. In this paper, a trial implementation in a 20-people test group is proposed, which will be implemented in the entire organization later.

6.1. Contact the Manufacturer

The first step in the implementation would be to contact the manufacturer. A close collaboration leads to reduced costs for both sides: the IHO has support for selection and data acquisition from the parts to be manufactured by RP techniques, and the manufacturer can obtain data directly from the customer in harsh conditions and offer feedback of the vehicle development process. For successful implementation, contact the manufacturer as early as possible.

6.2. Selection of Potential Parts to Manufacture

Once the manufacturer has been contacted, it is possible to proceed with the part selection. In this step, parts with mechanical and structural similarities to parts manufactured with RP techniques (in other words, parts that can be replicated by RP means) are chosen. In this step, the manufacturer’s help is vital. Other criteria for selection can be cost, availability in remote areas, and reliability.

6.3. Part Acquisition

Keeping in mind the characteristics of the spare parts to manufacture (dimensions, material), it is necessary to purchase the RP manufacturing equipment—and the RE equipment if applicable. It is important to keep in mind that it is meant to be transport: it should be lightweight and compact if possible.

6.4. Assembly and Equipment Calibration

Once the equipment is selected, a period of time is needed to ensure operability. The assembly of the equipment, the calibration, and a first training are the main steps in this stage.

6.5. “Preventive” Scan of Parts Susceptible to be Printed

Once the spare parts are selected, it is necessary to acquire the point cloud to build an STL file that the RP printer can read. This can be done in cooperation with the manufacturer (that may be able to provide the STL files) or independently from the manufacturer using RE equipment. The shipment to the emergency site of RE equipment is not necessary if the spare parts are characterized earlier, but if there is low confidence in this stage, additional efforts should be made to ensure the shipment and to be able to produce the necessary parts on the emergency site.

6.6. Replacement Parts Manufacturing

The next step is to manufacture with the RP equipment the selected spare parts. In this step, the focus is in checking that part building is correct and the product is similar to the original part.
6.7. Replacement on Vehicle and Performance Trial

Once the spare part is manufactured, it can be changed in a vehicle available to check the performance of the part. Even though this will not give an estimation of the reliability, it can be used to identify major performance issues: the part does not fit in, it is cracked after full accelerator pedal, lack of torque, and so forth. With this test, major failures may appear, but it does not ensure reliability. In part validation, the manufacturer’s support is needed.

6.8. Training and Support

The team responsible for the implementation should receive a detailed course covering the manufacturing procedures, the part scan, and how to resolve any incident or failure. Channels for requesting support should be clearly defined and available at launching time.

6.9. Packaging

To guarantee that the equipment can be shipped whenever needed it is necessary to contemplate the packaging. The packaging must allow the shipment with any contingency. The packaging should be isolated (waterproof is highly recommended) and must protect the equipment from any fall, occupying the least space possible.

6.10. Pilot Program Launch

Once these steps are followed, the equipment is ready for the pilot program. This is meant to test in the field the capabilities and the potential errors in the deployment of this new manufacturing program. In an emergency mock-up, the RP equipment is sent to a long-time IHO location. This site should have a working spare part replacement infrastructure (communications, mechanics, and spare parts available); therefore, if the pilot program fails, there are other possibilities, and the IHO operation will not be compromised.

6.11. Transport and Calibration

Once a location has been selected, the equipment and the needed personnel are transferred. Once the equipment has arrived, it is necessary to perform the system calibration. A first test part should be produced to act as a model. This part will be measured in detail to make sure all settings of the equipment are okay, and it will be sent to the headquarters to further measure and test to ensure that the same performance is reached in the future equipment locations.

6.12. Judgment and In-Use Life

In using the RP equipment during the emergency mock-up, a detailed evaluation of day-by-day and long-term operations must be performed, that is, manufacturer time of response and answer quality, problem identification gap, part manufacturing time, coherence new part–previous part, durability, vehicle performance, and so forth. Once the analysis is made, a go/no-go judgment must be made: if the problems identified can be resolved and the risks are controlled, the equipment is ready for deployment and can be used in a real emergency.

If it is decided to proceed using RP techniques in spare part manufacturing, the deployment of additional RP equipment can be initiated, taking into account that an effort in training IHO personnel is needed to ensure good operation on the emergency sites. Next steps should focus on the opportunity of using this technology for additional applications in emergency sites.

7. ADDITIONAL USES TO RAPID PROTOTYPING EQUIPMENT

In this paper, the use of RP techniques has been introduced to reproduce spare parts. Nevertheless, this is only but one of the possible applications of this technologies in an emergency area. RP technologies can be used to produce designs to improve current agricultural processes, sanitation, and healthcare. It can also be used in producing low-cost emergency housing, boats, and to manufacture prosthetic limbs and orthopedics (Thilmany, 2010).

RP for humanitarian aid is not a fully explored field, but there are some initiatives to use it for social purposes. The 3D4d challenge (3D printing for development) opened a door for designers to use RP technologies to provide solutions for current social issues, such as water filtration and energy supply (3D3D, 2012). Another initiative, leaded by Myminifactory and Oxfam, called for designs of hand-washing...
devices to produce RP equipment with the purpose of improving sanitation in developing countries.

In addition, free source RP equipment is more common and available to the wider public each day, making it easy to own an RP printer. As a consequence, a growing number of do-it-yourself designs are being developed, and some can be accessed online in RP enthusiast forums. RP CAD models for pipes, lamps, safety devices for electrical installations, and thermostats can be useful in developing areas and in emergency situations.

It is the view of the authors that even if the cost of purchase and transport of RP equipment to an emergency site is not justified for the production of spare parts (i.e., few vehicles in the area, high availability of workshops), the deployment of RP equipment is already necessary to support these applications.

8. CONCLUSIONS

Increasingly, RP technologies are being used to produce prototypes or final parts. This paper commented on its main advantages, among which are high flexibility of manufacturing and process automation and its limitations (such as material).

Humanitarian aid operations can improve their logistics supply chain by adapting industry advancements. The need for humanitarian aid is normally located in remote areas, and transportation is one of the main costs an IHO has to face. Also, in case of an emergency, limitation of transportation can be an issue, and logistics operation needs to focus on primary goods to help the affected.

Last mile vehicles are a scarce resource in an emergency operation. If a vehicle is damaged, it delays the transportation of goods to the population. IHO needs to have agile repairing systems to ensure the full availability of vehicles. In this paper, RP is introduced as a suitable solution to the spare parts supply for last mile vehicles in case of an emergency. RP can reduce lead times and ensure a higher rate of availability of the vehicles. Also, this paper emphasizes the need for collaboration between manufacturers and IHO to provide a real-time diagnosis and repair of vehicles to ensure humanitarian aid resources reach the ones in need as quickly as possible.

References


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Q2: Author: Please add corresponding author.