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Procedia CIRP 32 (2015) 70 – 75
www.elsevier.com/locate/procedia

The 5th Conference on Learning Factories 2015

Realization of a learning environment to promote sustainable value creation in areas with insufficient infrastructure

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Abstract

To increase the rationally demanded sustainability with its ecologic, environmental and social dimensions, innovative technology shall be exploited. For example waste can be used by means of closed loop material cycles for the production of new products. The understanding of such material cycles can help to deal responsibly with resources. Considering the limited awareness of more than seven billion humans on globe about the sustainability challenge, the teaching and learning productivity has to be boosted to hitherto not achieved levels. Complex interdependencies have to be scaled down to daily life experiences, so that people of different skill levels or even laypersons can draw a practical benefit and become capable of self-sustainable value creation.

How locally available plastic waste can be used for the production of new products in areas with insufficient technical and social infrastructure is explained in detail on the example of the mobile learning environment CubeFactory. This mini-factory was designed to support knowledge transfer for sustainable manufacturing competencies, independently from the need of any infrastructure. In this context, the term „infrastructure“ contains all technical as well as social necessities needed for production. These may be the access to a durable energy and material supplies, as well as the access to machine tools or knowledge. Sustainability utilizes all elements to its advantage to serve as a beneficial tool for the society, the local economy and the environment. The CubeFactory represents an example of how to produce on local level what is immediately needed. It integrates a 3D printer as a manufacturing tool, a recycler for the filament production, a solar-powered energy supply and the knowledge for the application of this resource-saving technology.

Peer-review under responsibility of the organizing committee of 5th Conference on Learning Factories (CLF 2015)

Keywords: Mini-factory, Learnstrument, Sustainability, Closed loop material cycles, 3D printing, Self-sufficient manufacturing system

1. Introduction

Sustainability is considered to be an important key to improve social equity while avoiding the environmental risks and ecological scarcities. Sustainability can be understood as a concept to describe the use of a regenerative system, while meeting „the needs of the present without compromising the ability of future generations to meet their own needs“ [1]. Nevertheless, most countries have recognized the importance for such a balanced system, but a global and binding strategy to enforce this is still missing. At least since the *United Nations Conference on Sustainable Development –Rio +20* the question has arisen to what extent the international community has a legitimate interest in the enforcement of measurable goals and is willing to represent a strong position on social and environmental issues. Many scientists rather advance the view that those debates detract from the urgent problems by focusing our attention on misleading subjects. Perchance the key problem is more an entirely anthropocentric once, and perhaps it is not to set new limits of pollution than rather to strengthen our set of values and the way the global community is related to the natural world [2]. Regarding to this agenda the founder

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doi:10.1016/j.procir.2015.04.095

of the *Centre for Interactive Research on Sustainability (CIRS)* Prof. J. Robinson notes in his paper „Some thoughts on the idea of sustainable development“ that he suggests on the long-term it is more promising to promote “new forms of social learning” for having “better-trained-citizens”. He recommends to “focus its attention more strongly on developing the knowledge, tools and training required to address the challenge of sustainability” and argues for an integrative approach that is action orientated and goes beyond technical fixes to engage local communities in a new way [3].

The mobile mini-factory CubeFactory pursuing this approach of engaging local communities, but with a particular focus on the qualification of unskilled people for the application of sustainable value creation in areas with poorly supported infrastructure. Just as value creation targets to enrich the shareholder, Sustainable Value Creation tracks an almost identical goal, but a more multifaceted and compatible one, involving economic, social and environmental concerns. The value-added performance is affected in a dominant, balanced and prospective way to create competitive advantages for a measurable profit and a community benefit without harming environmental needs.

2. Approach

The CubeFactory is an infrastructure independent production and learning factory that carries everything needed for sustainable production in itself – the tools, the suppliers and the knowledge. It is formed by the modules manufacturing (Fused Deposition Modeling (FDM) 3D printer), material supply (plastic recycler for the production of 3D printer filament), energy supply (solar cells) and knowledge transfer (tablet interface). These modules are integrated in a compact 1m^3 large extendable cube that can be used worldwide with only a small amount of prior knowledge (Fig. 1).

Fig. 1. Realization of the learning environment CubeFactory
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2.1. The Approach of Learnstruments

In the development special focus of the CubeFactory was laid on the application by unskilled users. For this purpose the concept of Learnstruments was implemented, a research field of the CRC 1026 Sustainable Manufacturing, in which the CubeFactory is located. The Learnstrument is a user-centered design approach to combine learning and working to increase the employee’s productivity and awareness, in this case the awareness for sustainable value creation. “Learnstruments are objects which automatically demonstrate their functionality to the learner. They consist of aspects of cognitive stimulation and emotional association with new and existing ICT and design approaches for productive mediation” [4]. This concept prevents an intuitive learning cycle that covers all aspects of perception and processing continua to increase the learning productivity and to reduce human activity-oriented errors. The user is methodically supported in knowledge creation by the elements of motivation (experience), awareness (reflection), systematic knowledge (abstraction), skills (practice), innovation and transformation (experimentation). This appealing method enables the user to expand his knowledge and skills independently and is aimed at both, beginner and advanced. The CubeFactory itself can also be regarded as a Learnstrument.

This learner-centered design approach was directive in the design of hardware and software. The aim was to design both elements in a way, which is appealing and easy to use, especially for untrained users to tap into their functions and benefits immediately. Owing to the novelty of this approach it was impossible to resort to a finished software solution that is suitable to the requirements. Therefore custom software was developed and programmed to form the link between physical and virtual learning respectively value creation environment. For the selection of other components the use of Open-Source applications was preferred. This discloses the potentials of open standards, dropped licensing costs and provides a broad supporting community.

2.2. Mediation Content

2.2.1. Closed Loop Material Cycles

The main aspect of the teaching of sustainable value creation is the descriptive inclusion of a closed loop material cycle. Sustainable economies require innovative products as well as processes with a life-cycle-orientated way of thinking and acting. This does not end with the customer, but continues with the disposal of goods and the further handling of materials.

In the case of the CubeFactory the customer must be enabled to integrate key aspects of sustainability into products and production, with a “Cradle to Cradle” way of thinking. It starts from the very beginning, like the planning and designing of products and processes, up to the manufacturing, the use and the end-of-life treatment. This does not only take into account the manufactured products, but also the equipment and materials. For this purpose, the approach of a closed loop material cycle is integrated in the CubeFactory and is reflected both, in the selection and in the arrangement of the manufacturing equipment (Fig. 2).

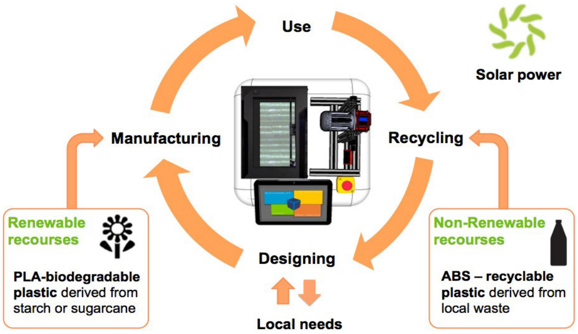

Fig. 2. Schematic illustration of the applied closed loop material cycle

The user is led from the start to focus his product design on the use of sustainable production techniques like 3D printing (3DP) and the further reuse of material in the provided desktop recycler.

The understanding of the complex content and the implication of the use of primary and secondary raw materials is to be taught. This does not only include the limits of access to virgin, non-renewable resources, but also the increasing material demand of more people with a rising standard of living. Non-renewable resources worn out after usage need not be deposed of, but can be regained in the material cycle. By recycling local domestic waste like PET (Polyethylene terephthalate) bottles, ABS (Acrylnitril-Butadien-Styrol) based plastics or unused printed goods, materials are kept in the cycle or can be locked in.

The resulting ecological and economic benefits for the user by the reuse of resources are highlighted in the CubeFactory's learning environment and serve as a motivation for their practice. For instance, the recycling of waste streams can reduce pollution, shorten transport routes for material supply and cut the emission of CO_2 while providing an inexpensive raw material. Especially for developing countries or areas with an underdeveloped or served infrastructure the local production of consumables for 3DP can reduce storage requirements and therefore the commitment of capital. This further increases independence regarding supra-regional distribution channels.

2.2.2. Sustainability

In order to maximize sustainability benefits for the user, advantages of small-size manufacturing equipment have been identified and integrated into the concept. Some are subdivided according to their dimension and listed below.

Environmental advantages: The promotion of a closed loop material cycle and its ecological advantages has been previously described. Due to the small size, the mobility and the substitution of traditional manufacturing equipment with desktop machine tools, the CubeFactory is assumed to have a reduced ecological footprint. This assumption is based on the reduced consumption of energy and resources by self-sufficient supply, for example the integration of the desktop recycler as a material supply. By powering the CubeFactory off-grid with solar cells, an environmentally acceptable energy supply is ensured. As products are produced for local markets distribution channels can be shortened. This is accompanied by a reduction of CO_2. The promotion of a "produce-on-demand" manner can be used to avoid overproduction. By the use of a modular structure and a "plug-and-produce" mode, components can be easily replaced or updated. This fosters reusability.

Economic advantages: To create the most economic benefit out of sustainable value creation, the CubeFactory has to offer a competitive alternative to traditional manufacturing equipment along with improved performance. This was achieved by implementing a desktop 3D printer, which is inexpensive in cost of acquisition and has a low energy demand. This desktop machine tool provides the possibility to produce customized goods at the price of mass-produced products; while the "produce-on-demand" procedure increases the flexibility and can minimize inventory risks for unsold finished goods. The energy-supply is done off-grid by solar panels and therefore causes no further costs. By including a desktop recycler and the use of locally available resources, the material costs are kept very low and lead to increased profitability.

Social advantages: The transfer of knowledge is considered as the main social benefit and was therefore integrated into the CubeFactory by a separate module. The comprehension of the complex correlations between sustainability and value creation strengthens not only the users but also the collective awareness. In addition, the learned operating skills and improved technical knowledge increase the workers abilities and thus the chance of a regular income. All applications and devices can be operated in an easy-to-use manner. Special knowledge is not required; it is completely integrated and communicated to the operator by the use of the CubeFactory.

Since knowledge in the broadest sense can be considered as a resource and the CubeFactory focus on knowledge transfer and far-sighted use of resources, this also applies to the content of this project. On the website www.cubefactory.org all construction plans, pictures and experience of realization have been documented and made publicly available. The CubeFactory is an open source project.

2.3. Modules

2.3.1. Knowledge Transfer

In line with the approach of Learnstruments the learning environment is designed as an intuitive system that is easy to use and provides the ability to enable also unskilled user to apply selected principles of sustainability, e.g. a closed loop material cycle. It has to meet two central tasks, the mediation of principles and awareness of sustainable value creation but at the same time mediate the machine's purpose and functions supported by the use of a touchscreen tablet computer.

For the design of systems for human-computer interaction (HCI), different approaches are existing. Shneiderman's heuristic of the eight golden rules of interface design provides an approach to improve the usability of an interface [5]. They can give a useful guidance, without claiming completeness, but being proven in practice for decades. Regarding to Dix et al. most approaches can be primarily differ in the dimensions generals and liability [6]. Therefore, the system should fulfill three important principles: learnability, flexibility and robustness.

Thus, the user can exploit the potentials of the system, the learnability of the knowledge transfer module is an essential criterion for the success of mediation. Therefore the structure and functions of the interface must be predictable, so that the user can suggest the impact of all his actions. At the same time he has to comprehend the impact of his past interaction with the system. For example dialogues should be designed such that a sequence of consecutive actions and their coherence are clearly comprehensible. This supports the feeling of acceptance of the system and helps the user to focus on the tasks set.

This experience-based processes can be strengthened if the system and its elements seems to be familiar or already known. For example, the shape and texture of a button can help to identify it as an input element or help to understand its function. Or the appearance of an object on the screen can be an indicator for the user that interaction is required. For this purpose, mechanisms of interaction are supposed to be generalizable, so already learned strategies may be consolidated in similar or new situations. This generalization is determined to a large extent by the consistency of the system, for example through a consistent design or by repeating substantial interaction mechanisms.

Another criterion to be met is the flexibility of the system. It should provide the user with different ways of interaction and prevent him from coercive measures such as forced dialogues. Tasks and processes should be interruptible and should offer the possibility of being continued at a later point in time. Also, the system should adapt to the users individual needs. This modifiability can be carried by himself, but also adaptively by the system.

The term robustness includes all the features of the learning environment that supports the user in achieving his objectives and helps him recognize his performance level [6]. On the basis of information presented the user must be able to recognize the system state, provide the opportunity to choose between different options or to take a step back. The user should have the opportunity to make any mistakes undo or restore old system states. This will make it easier to discover the systems functions and step back, if a task is unwanted.

To keep the attention of the user a robust system requires quick responsiveness. Waiting times should be avoided, longer computation operations should be visibly displayed or organized in an entertaining manner.

These rules and advices described above can help to create a robust learning environment. But in the end what counts for the success of a system is if the user is supported to achieve the goals determined. With its application the learning environment must support the user to understand the manner of the system and assist him in carrying out his tasks in the simplest possible way. The system has to be designed for the user and take into account any differences in knowledge, age, disability and technological diversity. By that a user-friendly structure and design can be made, that arouses curiosity and motivates the user to keep on learning.

2.3.2. Manufacturing

The 3D printer Ultimaker has to fulfill a central and significant role inside the CubeFactory. It is the essential value-adding tool. At the same time it is also an essential part of the Learnstruments that inevitably has to create a lot of attentiveness and to provide an easy-to-use and -produce manner.

To anticipate the Ultimaker meets most of the required properties. Firstly, it is a particularly sustainable tool. The used additive manufacturing method of FDM/FFF (Fused Deposition Modeling/Fused Filament Fabrication) can be perceived as virtually waste-free, placing material where it is exactly needed, it is near-net-shape and requires no further finishing. The Ultimaker is, like most FDM-printers, capable of printing with biodegradable PLA (Polylactic acid) plastics or ABS. In conjunction with the recycling device used ABS can be restored to working condition. Due to its low power demand of 120 W this 3D printer has a good energy efficiency that makes it highly suitable for the off-grid energy supply of the CubeFactory [8]. The comparatively economic price of €1200 as DIY-kit (Do-It-Yourself) makes it an affordable production tool and provides an inexpensive access into sustainable manufacturing, while reducing investment risks. Based on open source hard- and software, the user has an additional economic benefit resorting to cost-free software, the reduced risk of vendor lock-in, the advantages from the development of open standards or the support of a large community.

Considering the aspects of Learnstruments and the requirement of piquing curiosity the Ultimaker is built with a slim framework. Thus the user is able to examine the process as well as the progress in producing objects. Its simple design is considered to be user-friendly, to provide an easy-to-produce manner or an easy maintenance. Its design was engineered with a focus on using accessible standard components to provide a simple replacement or enhancement. By the use of the optional Ulticontroller the main settings and operations can be performed without the support of a computer, wherein the object data are stored on a SD card. Thus, the user can change settings very simply, experiment with the appliance and expand his knowledge and horizon of experience.

Comparing its technical specification with other 3D printers in this price range, further advantages can be highlighted. Its build volume of 21x21x20,5 cm (L/W/H) while claiming a desktop friendly footprint of 35x35 cm in combination with the fastest controlled horizontal acceleration in the market allows to print large objects very rapidly, processing a max travel rate of 500 mm/s. In contrast to many other printers both, translatory and rotatory motions are integrated into its parallel kinematics. By placing the stepper motors to the outer frame, the moving masses are kept low, thus the accuracy printing increased down to 40 microns in every direction [8].

2.3.3. Recycling Device

The limitation of non-renewable resources becomes an urgent requirement, in particular since the increasing scarcity of crude oil is associated with a rise in commodity prices. Although the direct economic impacts for plastics have been moderate, but the environmental impact, especially in developing countries, is hard to miss. A regulate waste disposal system is often insufficient available or is completely absent, so that waste is incinerated or disposed in the environment.

Therefore, the promotion of awareness regarding sustainability is of particular importance. It is this awareness to awaken, to explain the complex issues and to clarify causes and effects of non-sustainable behavior. To demonstrate the potential and value of recycling vividly the Home Recycling Device (HRD) was integrated into the CubeFactory. This desktop recycler has been designed for the recycling of thermoplastic domestic waste by turning it into new 3D printer filament. It is a cooperative development of the Technical Universities of Twente and Berlin made in 2012 and was one of the first fully functional small sized recycling equipment for 3D printer consumables (Fig. 3).

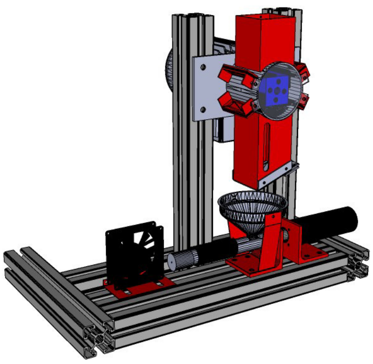

Fig. 3. Recycling module - Home Recycling Device (HRD) [7]

The steps of granulating and extrusion achieve the reconditioning. The material is granulated in a mechanical shredder by four rotating knives and temporarily stored in a reservoir. A hopper is used to feed the pellets to the extruder. This is designed as a screw extruder, in which the granules are retracted, compressed and discharged. To melt the granules an electrically energized inductor made out of a resistance wire supplies thermal energy.

To allow maximum flexibility in application, the HRD has been designed for both manual and computer assisted usage. All processes can be operated by a common laboratory power supply and controlled by means of intuitive and easy to use software. An Arduino board and a Windows application, running on a mobile tablet PC, do the latter. This can read various sensors, displaying the actual value of temperature, current or extruder speed and offers the possibility to control all relevant process variables.

The HRD is directly involved in the value adding process; it is the tool for the production of 3D printer filament. The filament can be considered as semi-finished product, stored for the next process, as well as finished product to be sold to other printer owners. This reduces the cost of production and can provide an additional income. As already mentioned, domestic waste is used as a locally available resource. That returns obsolete or dispensable products into the value creation process. Comparing the cost of 100 kg of sorted plastic waste ($1.00) with 1 kg of 3D printer ABS-filament ($25), an up lift ratio of 2500:1 is realized [9]. By producing local, distribution routes can be shortened or completely eliminated. Thereby production gets more cost efficient, can reduce the amount of waste and saves CO_2.

Thus the approach of a closed loop material cycle, is not only economic beneficial, but also environmental. A social benefit results from the increased awareness towards an environmentally sensitive way of living, from the raised income of small producers or from the training of local entrepreneurs for sustainable value creation. Especially in areas of insufficient infrastructure this kind of decentralized manufacturing can enhance the availability of production facility, since the consumables are produced on the spot and are not dependent on distribution channels. Is the subsequent use of produced goods made local, even a closed local loop cycle can be realized.

2.3.4. Energy Supply

To ensure an uninterrupted and economic energy supply in structural poorly served areas the CubeFactory is equipped with a high efficient solar system, using sunlight as a regenerative source. It is formed by the main components solar modules, energy storage, battery management system and AC/DC converter.

The solar modules are made using 25 high-quality polycrystalline solar cells per module attached to the CubeFactory's framework, mounted on 3D printed fixings. The particular advantage of polycrystalline cells is their high power density of $200W/m^2$, which is one of the most powerful available on the market. At very low solar radiation or diffused scattered light they provide a remarkably high-energy yield, thus they make low demands on installation site. To enable the best conversation of solar energy in times of increased degree of capacity utilization, the panels are designed to be detachable. They can be place side by side to use the entire surface of 2,45 m^2 with the best angle of radiation while the worker has the opportunity to produce standing in the shadow. The back sheet support plate is made of glass fiber-reinforced laminate, making it light with a weight of 3-4 kg/m^2 while having a high bending stiffness and durability. Even at high mechanical loads with a resultant partial cell fraction, the solar cells can perform their function properly. This makes them particularly suitable to the requirement of mobility and the associated vibration and shock loads. At the same time they also meet high safety standards.

To meet demands of a high capacity but secure energy supply, rechargeable Lithium-Iron-Phosphate ($LiFePO_4$) batteries were installed. Due to the solid electrolyte and the cell chemistry, $LiFePO_4$-cells are considered to be intrinsically safe and robust, viz. thermal membrane fusing respectively explosions as in lithium-ion batteries are excluded. Compared with Li-Ion batteries they have a higher power density (3000 W/kg), a high energy density (0,105 kWh/kg) and thus a higher load capacity. Owing to their cycle stability with 3000 cycles at 80 % DOD (Depth Of Discharge), they have a long economic lifetime and thus low operating costs. By dispensing with Cobalt $LiFePO_4$-batteries have an improved environmental compatibility.

3. Conclusion

This paper presents a concept to enable people for local sustainable value creation by the use of local available materials, taking into account low prior knowledge, skills and qualifications. An improved understanding regarding basic sustainable manufacturing competencies and recycling capabilities shall enhance the awareness regarding sustainability-related aspects of value creation, with particular focus on the efficiency and effectiveness of resources. All activities seek to strengthen communities by the exchange of knowledge following the principle *utilizing local resources by global knowledge*, because knowledge is the only resource that increases with use.

Acknowledgement

This paper is partly based on work, funded by the German Research Foundation DFG (CRC 1026/1 2012) as part of the Collaborative Research Centre 1026 Sustainable Manufacturing – shaping global value creation. Special thanks for developing individual parts go to Marijn Zwier, Arnout Oldenburger, Sharmaine Mannan, Christopher Carus and Dr. Steffen Heyer.

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