21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

TOWARDS A TOP-DOWN DESIGN METHODOLOGY FOR 4D PRINTING

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Abstract

An innovative trend promoted by the unique capabilities of additive manufacturing techniques is about the 4D Printing concept. It is the process by which parts embodying smart materials are printed, they are therefore able to react to changes in their environment. As a new way of thinking and manufacturing method, few is known about how to systematically bring such smart products ideas into reality. This paper discusses a general framework for designing 4D printed products. It delineates the research effort to be made so that designers are sufficiently empowered to design this new type of products. A methodology facilitating the consideration of smart materials is considered.

Keywords: Design for Additive Manufacturing (DfAM), Additive Manufacturing, Design methods

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 5: Design for X, Design to X, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

Firstly used as rapid prototyping processes, additive manufacturing (AM) techniques are now used to print end of use products. Indeed the applications of 3D printed parts can be found in a large spectrum of industries including automotive (Ilardo and Williams, 2010), aerospace (Uhlmann et al., 2015), electronics (Hoerber et al., 2014), and even health (Bartolo et al., 2012). Compared to conventional manufacturing, AM techniques provide unique capabilities. Owing to the layer-by-layer building fashion of these techniques, complex shapes that were too difficult or impossible to manufacture are now made possible at no significant extra cost or time. In addition to the allowed affordable geometry complexity, AM is also capable of material complexity. Actually the emergence of multi-material 3D printers leads to physical parts with almost any material distribution. Others capabilities such as hierarchical complexity (features of any length scale – micro-, meso-, and macroscale – can be integrated into a part's geometry) and functional complexity (fully functional mechanisms can be manufactured) are also the engines of the 3D printing revolution.

While this new manufacturing method is still in its infancy (despite being around since the 1980s (Hull, 1986)) and, therefore, not yet fully adopted, it has yielded another disruptive technology: 4D Printing (Tibbits, 2014; Momeni et al., 2017). 4D printing (4DP) is the additive manufacturing of multi-material – including particularly smart materials (SMs) – three dimensional objects; the fourth dimension being in reference to the ability of such objects to change their properties (i.e. shape, physical properties, etc.) and, potentially, their functionality over time after being printed. They owe such capabilities to the embedded stimuli-responsive SMs (Kamila, 2013; Bogue, 2014), whose properties change upon exposure to a specific stimulus or set of stimuli (e.g. heat, light, moisture, etc.). The ingenuity of 4D printed objects relies on the smartly designed interactions between geometry (or more generally configuration), materials (both conventional and smart ones) and energy (either a passive one such as heat or moisture or an active one such as current). Owing to the ability of 4D printed objects to transform (potentially in order to fulfil various functionalities), they can be seen as robotics without wires, sensors and actuators. This revolutionary technology is expected to be commercialized by 2019 (MarketsAndMarkets, 2015).

One of the most interesting mechanical properties encountered in the SMs realm is the shape-shifting capacity as a response to a specific stimulus. For instance, shape memory polymers (SMPs) or shape memory alloys (SMAs) can be thermo-mechanically programmed to assume a temporary shape and revert to a permanent shape once subjected to heat. This shape changing ability in SMPs has been the one mostly considered in 4DP studies thus far (Ge et al., 2013; Ge et al., 2014; Khoo et al., 2015; Mao et al., 2015; Zarek et al., 2015).

The customary way of thinking about and designing artefacts can be considered as an endurantist one. This means that an artefact wholly exists at each time, therefore exhibiting the same state and functionality over its lifetime. In a more and more competitive industrial global market context, driven by high profitability, versatile customers' needs and new concerns such as sustainability, environment friendless, a perdurantism viewpoint of artefacts would be more beneficial. Perdurant artefacts do only exist partly at each time; they exist through their temporal parts, and as such, are able to evolve over time. 4DP has made realistic such a philosophical vision of the physical world. An increasing number of studies (Momeni et al., 2017) are scrutinizing 4DP particularly as regards manufacturability. They do demonstrate through proof of concepts what is made possible by the new interaction of AM and SMs. However for 4DP to make it to industrial adoption, research efforts must be targeted at design methods, models, and tools as well. The purpose of this paper is to provide the foundations of what a holistic approach, to design 4D printed objects, should be. A focus has also been made on how SMs can be easily be used by designers. Section 2 reviews the work that has been done in this growing research area; the research efforts to be made so that 4DP can be easily considered by designers are highlighted in Section 3. Section 4 discusses the specific design issues related to smart materials, especially the mechanically active ones; finally conclusions are drawn and future work is stressed in the last section.

2 REVIEW OF 4D PRINTING ADVANCES

2.1 4D printing with SMPs

SMAs can achieve a relatively high strain actuation (around 10%), though they do have some drawbacks: they are brittle, have a poor fatigue performance (which means poor cyclic resistance) and are expensive to manufacture (even with AM) and machine; in addition large area processing with such materials is not all viable. On the other hand SMPs present many advantages; they can recover from strains of more than 400% (Wei et al., 1998). Polymer materials are tough, relatively cheap and easy to process on large surface areas. Besides they are available in solution, and they can be finely structured by considering processes such as hot-, liquid-, and photo-embossing, imprinting and lithography. Finally, they are infinitely chemically tuneable to achieve specific physical properties. Considering the AM process PolyJet®, SMPs can be seen as the so-called digital materials (which are materials resulting from various combinations of two or more materials and whose thermomechanical properties are different). Such capabilities have made SMPs, materials of choice in 4DP. Ge et al. (2013) designed and printed a type of smart composite termed as printed active composite (PAC), which is composed of a lamina fabricated by printing glassy SMP fibres in an elastomeric matrix and a layer of pure matrix material. The strain mismatch (when the fibres exhibit their shape memory effect) between these two layers is responsible of a bending motion (the phenomenon is termed as eigenstrain) in a way similar to how a bimetal works. PACs owes their smartness to the laminate configuration and a specific subsequent thermomechanical training process. By using the PACs, they designed and printed plates – which after being thermomechanically programmed to assume complex three-dimensional configurations (including bent, coiled, and twisted strips, folded shapes, etc.) – could recover to their flat shape once subjected to heat. Moreover the team printed a self-assembling structure. In a subsequent work (Ge et al., 2014) they used PAC as active hinges between rigid plastic sections to enable origami folding patterns. They developed a theoretical model to support the design process of the hinge configuration (i.e. length, fibre dimensions, etc.) and in the thermomechanical programming steps. Using their model, active origami-like parts (including two origami airplanes, a box and a pyramid) were then fabricated. These parts returned to their original flat shape once immersed into hot water. In addition they printed a box which after being deformed to a flat plate recovers the box configuration once heated. The PAC hinges were fabricated by creating their computer aided design (CAD) model including the fibre and matrix configuration.

SMPs are characterized (among others) by their glass transition temperature Tg (i.e. the temperature at which the shape recovery effect occurs); they are chemically tuneable, so are their Tg. SMPs with different Tg, exhibit their shape memory effect at different times when subjected to a temperature higher than all the Tg. Using that, parts exhibiting sequential shape recovery have been designed and printed (Mao et al., 2015; Yu et al., 2015b). The parts include a helical structure, an inter-locking structure and an interlocking box. The basic idea of their approach is that by printing SMPs with carefully chosen Tg at specific locations of a part, sequential shape recovery (after deformation from the permanent shape) can be achieved. SMPs were used as hinges to perform folding. The helical parts were printed in their helical shape; they were deformed to a line shape at high temperature and cooled. Once immersed in hot water they reverted to their original shape in a sequential way and without collision. The shape recovery scheme was similar for the interlocking box. The ability of the used 3D printing techniques to generate digital materials is at the core of the success of such smart objects.

Most of the current studies of 4DP consider it in a multimaterial fashion, that is the manufactured artefacts are made of at least two materials; SMs sections are selectively combined with conventional ones to achieve the desired change. Another approach, less considered, consists in using a single (smart) material for the whole item. This approach has been considered by Yu et al. (2015a) who printed parts exhibiting multi-shape memory effects, that is parts taking more than one temporary shapes at different times. The parts were printed using the PolyJet technology. Similarly Zarek et al. (2015), used the stereolithography (SLA) process to print items totally made of SMP; the printed items include, among others, a stent recovering from a fully compacted state to a deployed one, an Eiffel tower recovering from a 'crushed' state to its actual shape, and a bird whose wings unfold once it is subjected to heat.

2.2 4D printing with other smart materials

Another family of SMs that is of interest in the 4DP domain is hydrogel. These materials work in liquid environments and owe their smartness to their ability to swell or shrink in response to environmental stimuli such as heat, change in pH or even electric field. Using a bioplotter (i.e. an extrusion process based 3D printer that processes biomaterials) and a thermally responsive hydrogel as ‘ink’, Bakarich et al. (2015) designed and printed a smart valve to control water flow. Parts of the valve were printed with the hydrogel, and others were with rigid polymer. In water at 20°C the hydrogel parts swell and water can flow through the valve. Water at 60°C leads the hydrogel parts to shrink and block the water, reducing the flow rate up to 99%. Reversibility was demonstrated with cooler water flowing through the valve normally and again hot water being blocked.

Water (or humidity) can also be used as a stimulus to trigger reaction in structures. Indeed hydrophilic polymers are another family of SMs that can absorb water to increase in size. Using a hydrophilic UV curable polymer as the active material, Raviv et al. (2014) designed and printed self-evolving complex structures. Their approach was based on the design of three deformation primitives including two stretching primitives and a folding one. These were embedded as active segments within deformable structures. The printed structures include: 1D part in the shape of the connected letters “MIT” and converging to the shape “SAL”; 2D grids deforming into a sinusoidal wave, a hyperbolic surface or a saddle like shape.

It is worth noticing that thus far only SMs which are mechanically active, that is, whose response generates strain, have been mostly considered for 4DP. However, as will be shown in Section 4.1 the spectrum of SMs responses is much larger. As a matter of fact, nearly all the definitions – provided in the literature – are related to shape or form change. Considering a larger view of the concept Pei (2014) provided another definition: it is the “the process of building a physical object using appropriate additive manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-materials with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time”. Given such a definition, 4D printed products could be made of thermochromic material, or piezoelectric material as shown by (Woodward et al., 2015).

3 A VIEW OF 4D PRINTING FROM A DESIGN PERSPECTIVE

The aforementioned 4DP studies fully demonstrate the feasibility of parts imbued with intelligence and which change their characteristics as a response to changes in their environment. However for this breakthrough in manufacturing capabilities to be fully established, future challenges in design methodologies are to be taken up, so that designers can be empowered to develop 4D printable products. Design considerations in these studies are (when they exist) rather bottom-up approaches, which generally consist in (i) characterizing the smart materials behaviour, in regard to changeability, stimulus, constitutive behaviour, and programmability (that is, how they should be trained in order to perform a specific change), (ii) *Ad hoc* design of mechanisms embodying the characterized smart materials and which are used as active components, and (iii) design and printing of smart objects either just for the purpose of demonstrating the potential of 4DP (as it is in most of the cases) or for illustrating a smart useful functionality (Bakarich et al., 2015).

While conventional design methodologies are fully established and validated for single state artefacts, they are not suitable for products developed with the 4DP technology. Indeed, since the essence of 4DP is about “…harness[ing] the huge potential of 3D printing to generate self-transforming structures with complex geometry” (Raviv et al., 2014), it entails a paradigm shift in three main areas: manufacturing processes (shift from conventional subtractive processes to AM processes); products’ configuration, which are no longer thought about and designed to be inert but are smart structures with the ability to transform in order to perform different functionalities or an enhanced functionality; moreover conventional materials are now combined to or even replaced by smart materials to allow products to sense and react accordingly to their environment. Designing for 4DP would then require investigating and mastering three main areas including design for AM, transformable product design and design with smart materials.

For the 4DP technology to be established, besides hardware challenges (materials, processes, etc.), others intangible challenges – especially design wise – are then to be overcame. How do we produce objects’ designs that are efficiently suited for AM processes? How a product is well designed to assume various states and potentially to fulfil various functionalities? How is the knowledge about the smartness of smart materials, made effectively available to designers? In order to tackle these design issues, we envision a holistic approach to how a 4D printable product should be designed. The purpose of such framework is not to design automatically, but to create methods, models and tools so that, given a design problem to be solved by 4DP, the designer knows what to do, when, and how. Such an approach entails:

- ***A design for changeability methodology***. Inherent to a 4D printable objects is the ability to change state. According to the various SMs' behaviours change may be sought for different purposes:
  - Change in shape or more generally in configuration. Such change is the one that has been the most researched in 4DP. Design methodologies such as those developed through the *Transformable Design Theory* (Singh et al., 2009) may be refined to suit the design needs of such products.
  - Change in mechanical properties such as viscosity, or stiffness.
  - Change in optical properties such as colour made possible by chromogenic materials (whose colours change as a response to some stimuli), or light emission made possible by luminescent materials (which emit light when upon excitation).
  - Any other changes made possible by stimuli-responsive SMs.

Given the states to be assumed by the product along with functional requirements, the methodology would provide a change-oriented context (or representation) consistent with how change is sought in the product to be designed. Such a representation would act as a backbone embodying a change strategy providing locations of where a smart behaviour (owned from the embedded SMs) should be within the product so that the triggering stimulus (or stimuli) lead(s) to the desired change.

- **The integration of the SMs behaviours in the design process**. An environment dedicated to design and simulate active components (including actuators and other components exhibiting a smart behaviour) made of SMs and taking advantage of freedom allowed by AM. In addition to design-oriented data on SMs, such environment should provide tools and methodologies allowing the definition of the materials distribution (up to functionally graded material manner) so that the desired change is effectively achieved.
- **A design for additive manufacturing (DFAM) methodology**. As a relatively new manufacturing technique, additive manufacturing is barely being considered under the light of design theory and methodology (Ponche et al., 2012; Rosen et al., 2015; Simpson et al., 2016). 4DP entails the use of AM as the manufacturing process. Designing an item to be 4D-printed must therefore abide by the selected AM process constraints – so that the item is seamlessly manufacturable – and must leverage the process capabilities – so that the item's performance is optimized. Constraints related to AM include: achievable dimensions, support structures, surface quality, etc. In the regards to AM capabilities, it can be seen in the shape's simplicity of the thus far 4D printed items, that the only one AM characteristics that has been considered is the material complexity. The performance of the items (e.g. actuation) can be improved by considering shape complexity for instance, as it has been shown in (Maute et al., 2015) where topology optimization has been considered for the design of actuators made of SMPs. Other AM characteristics, such as hierarchical complexity and functional complexity, may also be considered. In order to take full advantage of the design freedom allowed by AM and to also take into account its constraints, a design methodology dedicated to AM should be used to design the object's active and inert components.

An overall design problem statement of a 4D printable product can schematically be stated as "the object shall perform a [reversible] state change within *amount of time* from state A to state B when subjected to *stimulus X* in *environment Y*". The evolution issue is first solved by providing a change-oriented context, on which the detailed design is based. The product's inert structure is then designed with a design for additive manufacturing methodology. Using knowledge from smart materials' behaviour, active components – which are the ones sensing the environment and changing the state of the product – are also designed with the DFAM method. Such vision is depicted in Figure 1.

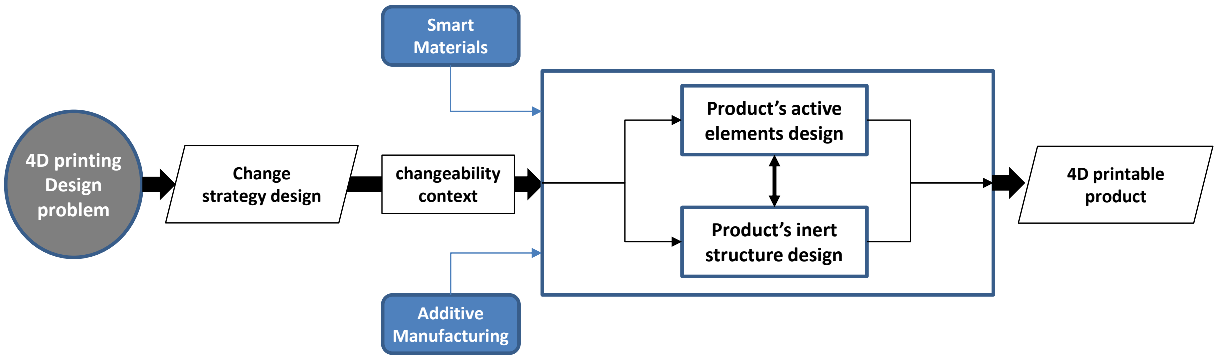

Figure 1. The proposed holistic approach to 4D printing oriented design

Critical to the efficiency of such an approach is the way SMs knowledge is brought to the designer. Next section discusses how SMs knowledge can be integrated in the design process.

4 DESIGNING WITH SMART MATERIALS (SMS) FOR 4D PRINTING

4.1 Description and classification of the SMs' behaviours

Most of the data available about SMs are dedicated to materials scientists, what could be an obstacle to considering them for non-materials' specialists such as architects and industrial designers. Such knowledge should be extracted and formally described with parameters capturing their working mechanisms. Figure 2 presents parameters that can be used for describing SMs a design database.

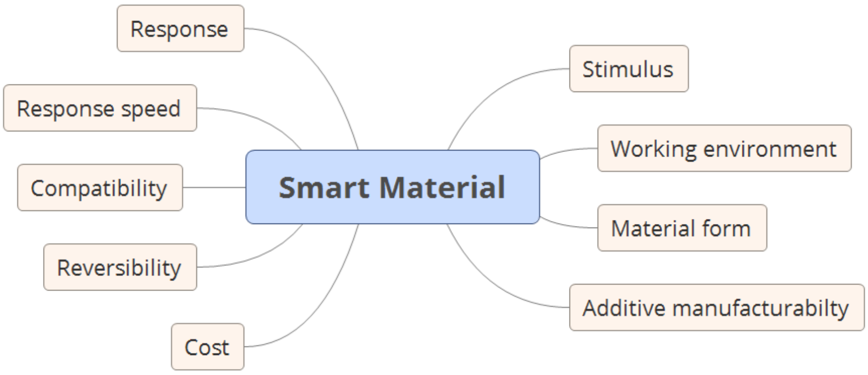

Figure 2. Smart materials' parameters

The SMs can be categorized based on these parameters, especially their response and the stimuli they are responsive to. Depending on the response, the categorization can be further refined. In the case of SMs that exhibit a mechanical response leading to a shape change, they can be classified according to the basic behaviours characterizing the response. Four basic behaviours can be distinguished: shrinking, swelling, bending and shape memory effect which is the most complex basic behaviours as it entails any arbitrary shape change.

Table 1 provides a classification of such materials along with the stimuli.

Table 1. A classification of mechanically responsive smart materials

		Elementary behaviours			
		Shrinking	Swelling	Bending	Shape memory effect
Stimuli	Heat	Hydrogels	Hydrogels		SMAs, SMPs
	Electricity	Hydrogels Electrostrictive materials		Conductive polymers	SMPs
	Magnetic field	Magnetostritive materials			SMPs
	Light	Photostrictive materials			SMPs

	Moisture (pH, salinity,etc.)	Hydrogels	Hydrophilic polymers		

4.1.1 Material distribution optimization

Using an optimization strategy taking as variables the spatial locations of the active material, and as constraints the type and amount of actuation of the chosen material and the way the stimulus field is received, the active material's distribution is optimized within the entire shape. This can be achieved through multiple material topology optimization (Gaynor et al., 2014), a scheme for functionally graded material, or multi-material lattice structures (Stankovic et al., 2015). Such a solution has been considered in (Weeger et al., 2016) where a methodology is provided to determine the distribution of SMP in a rod structure.

4.1.2 Shape change enablers selection

Available actuators or shape change enabler (SCE), which are combinations of active materials with either other active materials or conventional ones, may be chosen from a database and used at specific location within the shape. SCEs are basically active features which, when embedded in an object, can generate an alteration of its shape. More specifically they are physical embodiments of simple deformation primitive (linear shrinkage/expanding, bending, twisting, etc.), which are made of SMs and 3D printed. In addition printable self-locking/unlocking features such as the ones in (Mao et al., 2015) are also part of the SCEs. Others examples of SCEs include: PAC hinges (Ge et al., 2013) and the folding primitives presented in (Raviv et al., 2014) as bending SCEs, or the hydrogel components of the valve presented in (Bakarich et al., 2015) as both expanding and shrinkage SCE. As a consequence, a SCE is fully defined by the following set of characteristics:

- Shape change primitive.
- Smartness: this includes which stimulus it is sensitive to, how fast it reacts, and whether it is reversible or not.
- Mechanism: basically how it works.
- Material and the AM technique involved.

This set of definition characteristics can be used in two different ways. In addition to the selection use mentioned, it can also be useful as a formal way to specify the requirements for the design of a new SCE. In a way, similar to how standard parts' components such as bolts, nuts, or technical pair are available in some CAD software, a database SCEs with their tuneable parameters can be implemented into CAD software. SCEs are one of the major building blocks of the proposed framework; they can be used either for changing the shape of a component or for changing the relative position of two components. Figure 3 shows an example of how SCE may be used.

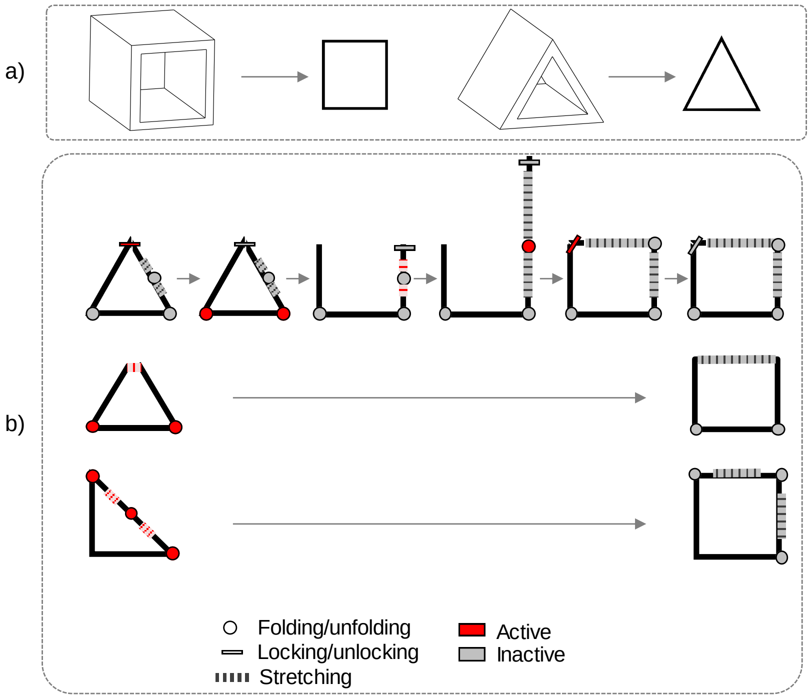

Figure 3. Shape change enabler selection for a change from a triangle-like component into a squared one. a) Shape abstraction – b) Various solutions for the desired shape change

5 CONCLUSIONS AND FUTURE WORK

4DP is a new disruptive technology born from the use of smart materials in additive manufacturing. This paper provides an attempt of a general framework intended to assist designers for 4D printed products. The framework give insights into how products can be imbued with the capacity of changing their states by themselves, taking advantage of stimuli-responsive behaviours of smart materials and the design freedom allowed by AM. Even though the proposed framework is intended to be general, in that the change in 4D printed product can be of various kinds, a particular focus has been made on the use of mechanically active smart materials in designing for 4DP. As a first attempt, the proposed approach can be improved in many different ways. Future work would include, inter alia: implementation of a computational framework assisting in designing with smart materials (including those non-mechanically active) in the way described in this paper, the possibility of simulating the surrounding environment, and particularly the triggering stimuli. The basic behaviours of the SMs have been considered in this paper solely based on their principle (shrinking/swelling, SME), however a finer and more realistic way to use their models would be to consider how much actuation can be obtained given an amount of the material. Furthermore, while AM does offer more design freedom and allow more complex configurations, it does also have its constraints and limitations. Such constraints ought to be taken into account. Future work can address this concern by adopting an approach similar to how manufacturable elements (MEL) have been designed in (Rosen, 2007).

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