LOWFLIP – AN INNOVATIVE DIRECT 3D PLACEMENT TECHNOLOGY FOR PLIES AND TAPES

Marko Szcesny[1], Frieder Heieck[1], Peter Middendorf [1],
Ricardo Mezzacasa[2], Xabier Irastorza[2], Harald Sehrschön[3] and Michael Schneiderbauer[3]

[1] Institute of Aircraft Design, Department of Aerospace Engineering & Geodesy, University Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany
Email: Szcesny@ifb.uni-stuttgart.de, Web Page: http://www.ifb.uni-stuttgart.de/

[2] TECNALIA, Transport & Industry Division, Mikeletegi Pasealekua 2, 20009 - Donostia-San Sebastian, Spain
Email: ricardo.mezzacasa@tecnalia.com, Web Page: www.tecnalia.com

[3] FILL GESELLSCHAFT M.B.H., Fillstraße 1, 4942 Gurten, Austria
Email: harald.sehrschoen@fill.co.at, Web Page: http://www.fill.co.at/

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Abstract

Breaking down the cost structure of state of the art CFRP part shows that about 50% of the costs are caused by labor & equipment as well as process energy consumption.
Therefore, the main goal of the EU funded project FP7 LowFlip (**Low** Cost **Fl**exible **I**ntegrated Composite **P**rocess) is to decrease these costs by introducing new technologies into CFRP production processes.
The LOWFLIP concept focuses on three main aspects:

1. Development of a new out-of-autoclave (OOA) prepreg system with snap cure capabilities [2]
2. Development of a direct 3D placement technology for plies and tapes
3. Development of energy efficient and fast heating tooling [3]

The main content of this paper is detailed information on a novel direct 3D prepreg layup process for automated production of large fiber reinforced parts. The LowFlip process, that is able to drape and compact UD prepreg tapes up to 300mm width directly into a double-curved tooling, is being introduced. Two large scale demonstrator parts from the truck and aerospace applications sector will be presented.

A solution for manufacturing small and medium sized parts with an adaptive pick and place end-effector is presented as well as some results of the practical equipment testing. The proposed demonstrator for the pick and place application, a CFRP – sandwich part for a car body main structure, will be introduced. Experiences gained during prototype manufacturing will be reflected.

1. Introduction

In the past decades there has been a significant progress in developing automated production technologies for carbon fiber reinforced parts (CFRP). However, the application of these methods for mass production across different industrial sectors has not been achieved by now for different reasons, e.g. high equipment invest necessary, too complex and unreliable machinery or low process flexibility.

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The main motivation behind the research work conducted in the EU funded program LowFlip is to introduce new materials and production methods in order to enable a widespread use of automated composite manufacturing technologies.

In different market studies [1] it is found that about 50 % of the costs of a state of the art CFRP part are caused by labor & equipment costs as well as process energy consumption. The remaining 50% result from material costs, as it can be seen in Fig (1).

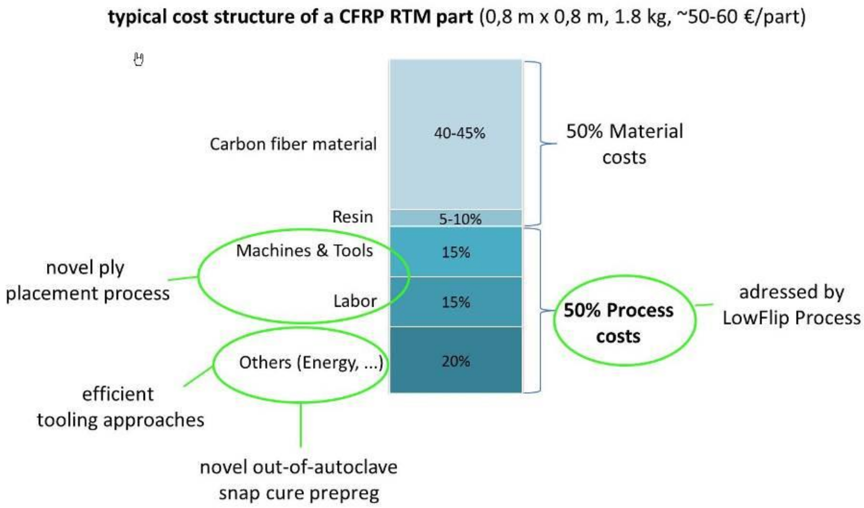

Figure 1 Typical cost structure of CFRP part and LowFlip impact [1]

Since material costs are mainly driven by resource and energy prices, they cannot be influenced directly by the components manufacturer. However, the costs for labor and equipment can be addressed by increasing the amount of automated processes in production. Also decreasing the energy consumption and cycle time of production processes can lower the costs per part.
The newly developed LowFlip production process focuses on three main aspects to improve the efficiency of the described processes.
On the material side a novel out-of-autoclave (OOA) prepreg system with snap cure capabilities was developed [2]. It allows saving process time and energy as well as simplifies the production process.
A novel direct 3D placement technology for plies and tapes was developed to improve the laminate quality beyond state of the art while keeping cycle times and equipment costs as low as possible.
In order to reach lower energy consumption and faster curing cycles, novel tooling solutions were developed. They excel in terms of lowest thermal capacity and achievable heating / cooling rates [3].
This article is focusing on the results of the production process development. Detailed information on the new developed prepreg material and tooling solutions are given in the papers stated below.

2. Development of the LowFlip process

2.1. Definition of objectives

Most of today's commercially available tape placement or fiber placement systems have one thing in common: Each machine is developed for processing a specified type of textile material, e.g. slit tape of certain width, equipped with resin type & amount of certain type etc. This leads to a strong dependency on the quality and availability of this material. Also, it limits the flexibility of the machine type's area of operations.

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A primary goal of LowFlip is to allow the use of a wide range of UD based prepreg materials up to a ply width of 300mm. The quality of the available prepreg material in terms of cutting / slitting tolerances should only have small influence to the reliability of the layup process. Obviously, the tape or fiber quality directly influences the laminate quality and should therefore be delivered in an optimal state. However, poor width tolerances or uneven impregnation levels of the UD material should not affect the layup process itself to work properly. In order to use the raw material as efficient as possible the targeted cutting scrap rate is less than 5% of the total amount of material used.

Another field in focus is to reduce the complexity of the sub components used for the machinery to the necessary minimum needed for a reliable and stable process. It is not necessary to assess aerospace accuracy standards, since LowFlip is aiming for applications in general machine building and transportation industry. The reduced component complexity is leading to a more robust layup process as well as lower equipment invests compared to state of the art machinery. This potentially enables small and medium-sized enterprises (SME) to introduce automated production technologies into their portfolio.

Due to the fact that especially SME have to deal with lots of different part sizes and geometries, the LowFlip equipment is designed in a modular concept. Thus it is possible to easily adapt to changes in parts size and geometry at reasonable costs.

It is difficult to produce small and complex parts as well as relatively large, less complex parts efficiently using one fixed machine setup. Therefore LowFlip combines different end-effectors with certain tooling approaches and materials to work as efficient as possible.

However, all components work as stand-alone solutions as well, if they have to be integrated into existing equipment lines.

2.2. Manufacturing equipment for small & medium sized parts

2.2.1. General design features pick & drape unit

When using advanced fiber placement machines (AFP) for producing small to medium sized parts, often two issues occur in this context: one is to keep the scrap rate low to save valuable raw material. This is usually hard to achieve by tape placement units, since they are limited to a minimum processable tape length, which is usually around 150 – 250mm. Also most AFP units can only cut straight lines perpendicular or under a certain angle to the placement direction.

Advanced fiber placement machines are able to selectively cut single tapes, allowing them to work with low scrap rates. The complex mechanical architecture of AFP machines leads to a second issue: especially on smaller parts they are hardly able to reach smaller curvatures or corners due to the size of the end-effector.

For these and other reasons the LowFlip approach to manufacture small to medium size parts is to use a robot guided, highly adaptive pick and drape end-effector using precut plies.

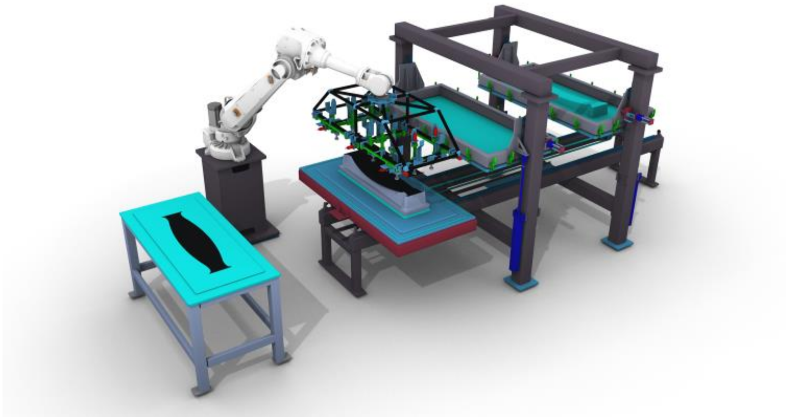

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Figure 2 LowFlip cell and pick & drape end effector for small & medium sized parts

The end-effector has a base frame made of lightweight components and can easily be adapted in size. It is equipped with multiple vacuum gripper units. Each gripper is mounted on adjustable axes and can change its position inside the gripper via software interface to match different take up and release positions during the pick and drape process. Since the grippers are able to move in two directions within the plane of the ply, they allow a three-dimensional pre-shaping of the ply or ply stack during the transfer to the tooling, if necessary. This further improves the layup quality compared to 2D layup and a subsequent forming step by forcing the fibers into the correct position on the 3D tool.

The placement can be done by using several pre-stacked plies for parts with low complex geometry. After a ply stack has been placed on the mold, a flexible membrane is used to fully shape and pre-compact the ply stack. If the geometry is too complex to achieve good draping quality using ply stacks, this has to be done ply by ply. In this case pre-compaction cycles using the vacuum membrane have to be conducted.

2.2.2. The LowFlip pick & drape process

In order to benchmark this process, a demonstrator part from the automotive industry has been selected, i.e. a crossbeam from a car body structure with a size of 1.2 m x 0.35 m. It is a structural sandwich part with two CFRP outer shells of 1.2 mm thickness of biaxial orientation.

A hollow metallic tooling with a large heat transfer surface is used. It is heated and cooled by a liquid and capable of heat up ramps of 8 K/min with 12 kW total heating power installed.

Since the CFRP part's sandwich core acts as thermal insulation preventing the upper plies to reach the curing temperatures, a self-heated curing membrane is being used to heat the upper layers. The heatable membrane is custom made and tested to withstand more than 50 curing cycles successfully without taking damage.

The LowFlip production process for small and complex parts is as follows:

1. Pre-cut and pre-stack 2x4 plies (300 gsm UD Carbon) at room temperature in 5min
2. Pre-drape the first ply stack of 4 plies of carbon UD prepreg on the tooling (80 °C) in 0.5 min
3. Pre-compact this ply stack via flexible membrane for 5 min at 80 °C
4. Place the foam core and the 2nd ply stack onto the tool in 0.5min
5. Heat up to 120 °C in 5min at 8 K/min
6. Curing of the part at 120 °C and 1 bar in 15 min
7. Cooldown of part and mold to 80 °C in 5 min at 8 K/min

The described process was already tested in some parts. Both the tooling and membrane systems as well as a lab scale pick and drape end-effector are already available.

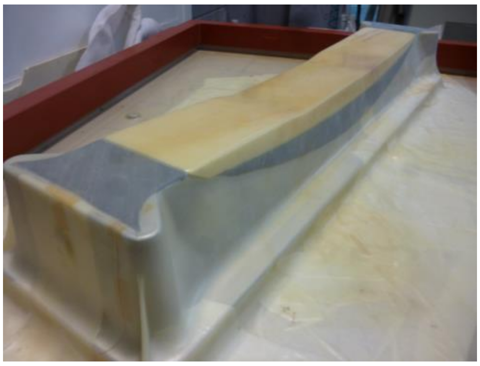

Figure 3 Compaction using vacuum membrane

Figure 4 sandwich demonstrator part

Excerpt from ISBN 978-3-00-053387-7

The fully operational pick and drape cell will be available in July 2016. It could also contain two curing molds with crosslinked heat transfer pipes. In this scenario the first tooling has a temperature level of 120°C at the end of the curing process and needs to be cooled. The second tooling is still at 80°C after the pre-compaction step and has to be heated. Now the heat transfer fluid is starting to circulate between the hot tooling and the colder one. As a result the first tooling cools down; while the second one heats up until the temperature equilibrium is reached. Then the tooling has to be heated / cooled further to obtain the process requirements. Thus, it is possible to partially re-use the thermal energy stored in the system. Also the total cycle time can be significantly decreased by conducting several process steps in parallel. The targeted overall process time per part is 15min.
The cross linking of mold cavities significantly raises the energy efficiency of the production cycle.

2.3. Manufacturing equipment for large sized parts

2.3.1. General design features of the ply placement cell

The LOWFLIP production cell for large parts is an industry robot based design and consists of interchangeable sub-components. Thus, it is possible to adapt the size of the accessible area with low invest of time and funding by changing only the necessary components. The demonstrator cell has a size of 8 x 9 m and will be ready for operation in July 2016.
The basic concept consists of two robots carrying one gripper unit each to pick up a pre-cut ply of prepreg from a cutting table next to the placement system. Both robots are mounted on a linear axis on the left and right side of the tool. A third robot is mounted in front of the tool and is operating the compaction roller for the layup consolidation. The standard ply width is 300mm, but can be changed to smaller width, if necessary. The mold itself is mounted on a rotatable tool tray to allow the deposition of material in any direction. It can be heated and is used for preforming as well as curing of the part. It is not necessary to transfer the preform to another curing tool after layup.

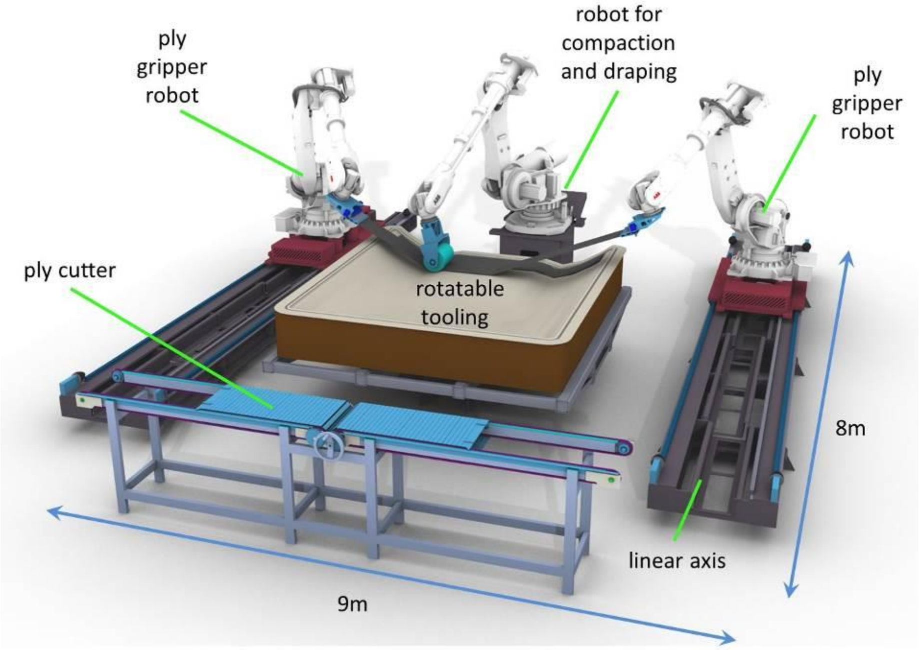

Figure 5 LowFlip production cell for large parts

Excerpt from ISBN 978-3-00-053387-7

The demonstrator part chosen by the consortium is a truck trailer front wall with a size of 2.5 m x 2.8 m and a double-curved surface. The structure is a CFRP monolithic part with a thickness of 4 mm and additional local reinforcements.
As a second demonstrator, a double-curved part of the outer skin of an A320 class passenger aircraft was selected with a size of about 1 m x 1.2 m. In this case it is a monolithic skin stiffened with stringer profiles. This demonstrator was selected to show the equipment's capabilities to include T-shaped stiffener profiles in an automated process. More details on this solution can be found in [3].

2.3.2. Draping state of the art

The process of draping textiles usually refers to placing the textile material onto a double-curved mold surface without wrinkles by allowing the adjacent fibers inside the ply to move by shearing. In order to have a proper part quality it is essential to equalize length deviations between adjacent fibers in a ply caused by the curvature of the mold.

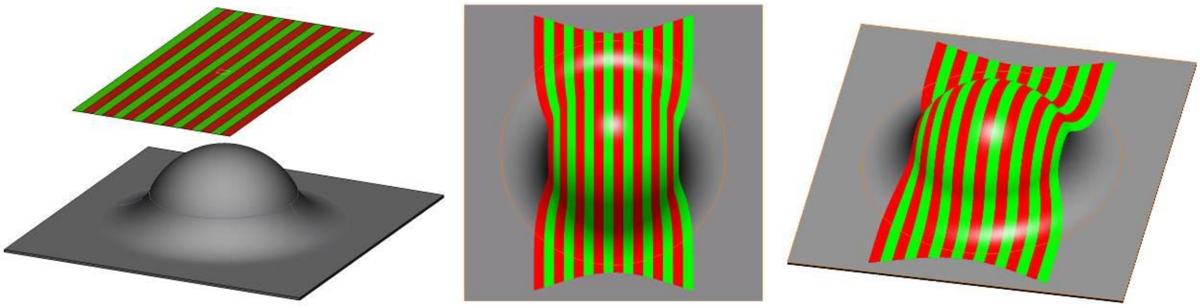

Figure 6 deformation by draping of an UD ply on half dome geometry

With AFP processes this equalization is normally done by steering the single tows at different speeds to achieve the desired tape length on every section of the layup path.
When using advanced tape laying (ATL) it is much more difficult to achieve wrinkle free laminates on 3D surfaces. Most ATL machines have to do a flat layup first because they use wider tapes in the range of 25 – 250 mm and are not able to manipulate the material's inner fiber architecture. After the 2D layup usually a transforming step into the final 3D geometry is performed via a press or stamping process. While the preform stack is being heated and transformed, the fibers in the stack will move from the 2D into the 3D architecture following the tooling's curvature. This movement is hardly reproducible from part to part because it is depending on many boundary conditions like internal friction, grade of material, temperature, etc. It often leads to wrinkles or gaps inside the fiber architecture of the part.

2.3.3. Details on the LowFlip layup process

The LowFlip process allows a direct and controlled draping of UD prepreg material directly into the 3D mold. Wrinkles and gaps between plies can be reduced to a minimum. Both butt joint placement of plies or overlap is possible.
The main sub components responsible for in-line draping are the grippers holding the left and right outer edge of the ply, as well as the flexible compaction roller guided by the consolidation robot.
The newly developed and patented gripper units are divided into segments which are able to individually move parallel to the UD fiber direction. The ply is placed in position slightly above the tooling and the compaction roller starts to compact the material on the mold surface at a predefined starting point with an applied pressure of about one bar. This starting point can be anywhere between the two grippers. The roller moves towards one of the grippers first.

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As long as there is no curvature perpendicular to the UD plies' 0° direction, all fibers in the ply to be placed have the same length between compaction roller and gripper. This is the case for a flat part of the mold in every placement direction (without draping effects) or at single-curved areas of the mold in the case of placing the ply in 90° direction to this single curvature.
If the compaction roller reaches a position on a double-curved area or if it does not move perpendicularly to the curve direction on a single-curved area of the mold, the projected track length of adjacent fibers between roller and gripper is not equal anymore. For this reason, the tension in the UD tape is also unevenly distributed. If not corrected, these length and tension differences inside the ply lead to wrinkles during the layup process, because the roller will simply overrun the wrinkled tape areas and compact them on the tool.
The gripper segments are designed in a way to keep the tension within a ply at a constant level even if locally the distance between roller and gripper varies. Because of the segmentation, they are able to move adjacent fibers relatively to each other by shear movement. The pneumatic system is working passively and is pulling the fibers at an adjustable level. As soon as length or tension deviations appear in the tape caused by the draping, the gripper elements pull back the fibers until tension is equalized. Fibers already tensioned will prevent further movement of the related gripper segments. The roller pressing down the tape on the tool over its full width prevents the tape from being pulled up from the tool. In this way the ply is always perfectly tensioned across to whole width while the compaction roller moves along its path on the mold. The amount of tension needed for equalizing is mainly depending on the matrix viscosity and UD material quality. It can be supported by parallel pre-cutting of the ply in critical areas.
After the draping step of one ply is complete, length deviations along the width of a ply can be seen at the outer borders of the tape after the gripper released it.

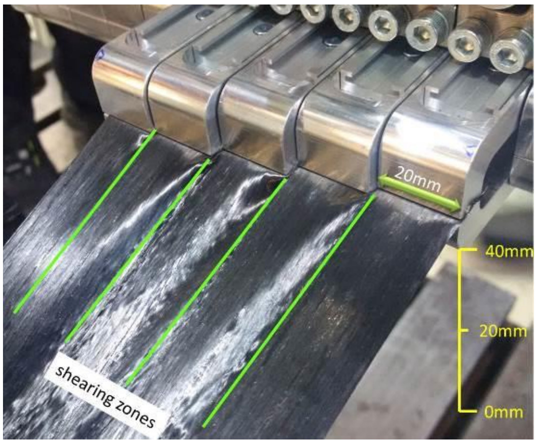

Figure 7 Gripper segments equalize tape tension

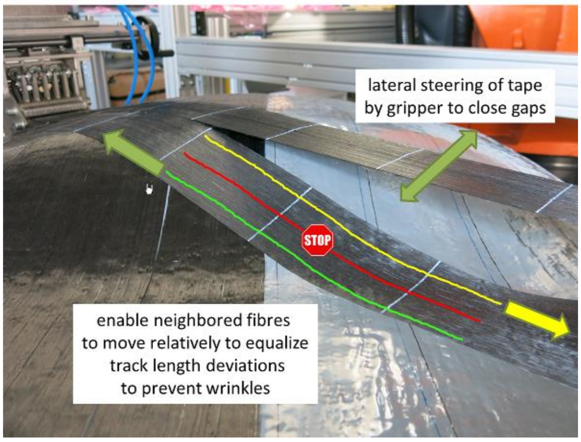

Figure 8 LowFlip draping mechanism

To avoid gaps and overlaps at the edges of adjacent tapes, the gripper is also able to perform a lateral movement to side shift the whole tape as needed to close the gap. In total, each gripper can be moved along 6 axes via the robot, which guides it to always keep the tape at equal tension and in the optimal position with reference to the compaction roller.

2.3.4. Some initial benchmarks

Up to now all tests and benchmarks have been conducted on the LowFlip lab-scale device. It is downscaled, but equipped with all functionalities of the industrial scale prototype cell which is currently set up. At the lab scale cell all moveable axes are to be driven manually, which prevents a serious benchmarking of the LowFlip process at the moment. Nevertheless, some basic process parameters can be estimated. Assuming a layup speed of 1 m/min, the layup rate is about 5.4 kg/h

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when using a material with 300 g/m² fiber areal weight and a ply width of 300 mm. An increase of the layup rate can mainly be achieved by speeding up the process and by the use of material with higher areal weight. Final benchmarks will be conducted with the industry scale prototype cell.
The achievable scrap rate is in the range of typical AFP / ATL system available on the market. It mainly depends on the size and shape of the part to be produced. In average it is in the range of 5% of the total used material.

3. Summary and future prospects

In the past 30 months of the LowFlip research project, a new and efficient method for automated production of fiber reinforced parts has been developed. The technical proof of concept for both production principles described above was validated. Sub-components of the system were designed and tested to a sufficient level to justify the production of the industry scale prototype cell in order to benchmark the whole process.

Moreover, the following related developments have been performed within LowFlip in order to achieve the goal of low cost automated composite production:

- A new out of autoclave prepreg material with snap cure abilities has been developed and tested successfully [2].
- New tooling approaches for energy efficient production of fiber reinforced parts have been designed and tested successfully [3].
- Until October 2016, the equipment will be extensively tested and benchmarked. Several demonstrators of each type described in this paper will be built and tested. Finally the overall process efficiency in terms of costs, cycle times and energy consumption will be summarized and published [4].

Acknowledgments

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