ENVIRONMENTAL ASPECTS OF USE OF ALUMINIUM FOR PREFABRICATED LIGHTWEIGHT HOUSES: DYMAXION HOUSE CASE STUDY

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ABSTRACT

The paper evaluates the environmental advantages and disadvantages of use of aluminium as building construction material for prefabrication of lightweight houses, by examining a case study of the Dymaxion House, designed by R. B. Fuller. The Dymaxion House was conceived as autonomous, transportable, lightweight, and disassembling unit. The predominant material in its envelope is aluminium. The production of this material has significant energy costs and environmental impact. However, aluminium is highly recyclable, long-lasting and has good performance characteristics, which, on the long run, diminishes the pressure on the natural resources and allows a significant reduction of quantity of used material. The paper re-evaluates its environmental impact on a larger time scale and takes into consideration all the aspects of its application. In addition, design strategies, (such as "design for disassembly") of the house are studied. Finally, paper provides some considerations about the "service industry" system, as conceived by R.B. Fuller (and also used nowadays in enterprises such as Interface Inc.), necessary for securing the house manufacturer's responsibility over the entire life cycle of the dwelling, thus guaranteeing high recycling rates.

KEYWORDS

prefabrication, aluminium, durability, dematerialization, recycling, environmental impact

1. INTRODUCTION

Aluminium is seen as one of the energetically costliest materials that are used in the building construction industry. However, the ways of use of these materials can significantly influence its environmental impact, once that the recyclability, durability and proper management have been considered in the design. Its properties such as lightness, resistance to rust, durability, etc. may be enhanced by its proper use and create a base for its more sustainable application. This paper will, through the case study of the Dymaxion House, try to provide some considerations for such a framework.

2. HISTORICAL OVERVIEW: DYMAXION HOUSE

Dymaxion houses were a series of projects for single family houses designed and realized between the 1927 and 1946 in the United States by Richard Buckminster Fuller. The common features of all the houses were:

- lightness
- use of the latest scientific and technological discoveries
- autonomy in functioning
- minimum use of material
- easy assembling and disassembling
- low cost
- transportability
- tornado resistance

The Wichita House, the second prototype (in a series of foreseen four) of the last stage of design of Dymaxion house (named by the Kansas town it was manufactured and assembled), was produced in Beech Aircraft factory and erected in 1946. Fuller reached and agreement with the local war airplane factory that, after the imminent ending of the Second World War, feared the cease of its activities. The proposal of R.B. Fuller to convert the factory into the housing production unit was seen as a possibility to continue the production and prevent the closure of the business and consequent loss of thousands of job posts.

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FIGURE 1. The Dymaxion (Wichita) House at the construction site, upon finishing the outer shell. (Source [5])

The airplane industry of that period used aluminium as one of the principal materials due to its good performances, lightness and strength, necessary for the aircraft technology. Fuller, who had experience in the US marine, considered that the housing industry should embrace the new materials and technologies, especially referring to new alloys, such as aluminium, and the features of the ships and planes, namely their lightness, mobility, and effective use of materials.

This extremely light house is of a circular plan, "hanged" from the central mast and anchored to the ground. The aluminium is used mainly for the outer shell, as well as for some structural parts.

3. GENERAL CHARACTERISTICS OF ALUMINIUM AND ITS ENVIRONMENTAL IMPACT

Aluminium was a material widely used in industry when the Dymaxion House was produced. Aluminium was isolated in 1855 and its massive production started in the beginning of the 20th century: in 1900 the production was of some 5.000 tonnes, in 1938 500.000 and in the Second World War it reached 2.000.000 tonnes due to its use in the aircraft industry [9]. Nowadays, around 24.000.000 tonnes are produced per year.

Energetically, the production process of aluminium is extremely costly: for a production of Kg of aluminium it necessary to use 165-260 MJ of energy, comparing with steel that requires 21-25 MJ, Copper 80-127 MJ, or zinc 47-87 MJ [2]. Energy costs represents approximately one third of the total production cost of aluminium.

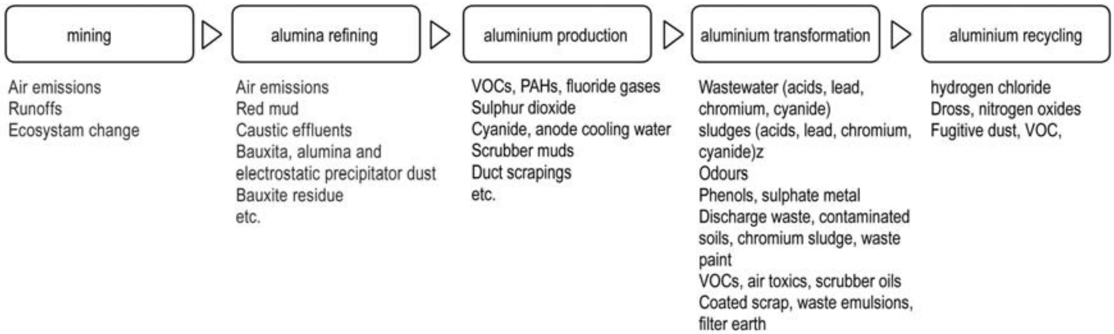
Aluminium is extracted from bauxite. Upon extraction from the soil crust, bauxite is refined into alumina which is then freed from oxygen in order to produce aluminium. The process is energetically costly due to the fact that the alumina (dissolved in a molten salt) needs to be put through the process of electrolysis which uses a great amount of energy. Additional environmental costs are produced by the need to transport the bauxite, often at long distances, since the extraction areas (such as Australia) do not count with cheap electricity (such as for example Scandinavian countries where the electrolysis is, for this reason, performed).

However, the performance characteristics made aluminium adequate for building construction purposes: it is resistant to rust, since it forms a thin layer of oxide on the surface that appears in contact with air and protects it from the corrosion. It is three times less dense then steel (2.7 vs 7.8 g/cm3) which implicates lighter constructions. Its tensile strength is of 49 MPa in pure state and up to 700 MPa if transformed into alloys. It is easily extruded, milled, glued and welded which facilitates its use and manipulation.

Aluminium is highly recyclable material and its recycling requires much less energy than its production: only between 5% and 15%. Basically, recycling consists of melting down the metal, without a need for energetically intensive electrolysis process. The material characteristics remain unchanged after the recycling process. The aluminium scrap value is high, which on the positive side helps it preserve its value at the end of the lifetime, but also makes it prone to theft [4]. In Europe 26% of used aluminium is integrated into buildings. The rate of the recycled aluminium use in buildings ranges form 7% for the cast alloys to 33% for the wrought alloys [8].

The main problem related to the use of aluminium in the construction, from the structural point of view is that aluminium is not as stiff as iron or steel and therefore these problems need to be overcome by design. Also, different alloys act in different manners, resulting in need for "trial and error" design process. Though resistant to corrosion when in pure state, aluminium gets susceptible to rust when

FIGURE 2. Emissions released to the environment along the aluminium lifecycle (Sources: [3] and [10])



alloyed. Alloying itself is needed to improve mechanical resistance and strength of pure aluminium. Contact with other metals leads to electrolytic corrosion.

4. GENERAL ENVIRONMENTAL ADVANTAGES AND DISADVANTAGES OF USE OF ALUMINIUM AS APPLIED IN THE DYMAXION HOUSE

Along the house's lifecycle, the use of aluminium implied the following environmental advantages and disadvantages in the Dymaxion House:

1. Production of the components (at the Beech Aircraft Factory)
   Advantages: In this case the use of already existing factory eliminated needs to build another facility, thus eliminating environmental impacts related.
   Disadvantages: the negative environmental impact related to the transformation of the aluminium (see Fig. 2)

2. Construction and transport:
   Advantages: small weight (around 2,700 kg) and volume (8.5 m3) therefore reduced storage and transportation environmental costs, reduced impact on the terrain due to the lightness of the house (foundations are reduced only to central mast and anchorage points), quick construction (only 3 days were needed) and low construction site impact since the components were prepared in the factory
   Disadvantages: high precession of the pieces (more possibility of committing a malfunctions leading to faster degradation of the components, which showed on the building site)

3. Occupancy stage:
   Advantages: low maintenance due to the use of unpainted and corrosion-free material, adequate cooling and ventilation due to the lightweight vent installed at the roof, which provided the house with natural ventilation
   Disadvantages: thermal insulation was almost definitely insufficient (aluminium is a good thermal conductor), poor water proofing due to the inadequately designed/executed joints between the roof aluminium sheets, general noise caused by rain or hail falling on aluminium roof and wall sheets

4. Dismantling and Recycling:
   Advantages: the building was designed to be readily demountable and could be constructed in another location. (In the particular case of Wichita House which was a trial version, the rivets were used instead of bolts which complicated the process of disassembly).

5. DEMATERIALIZATION AS MEANS FOR REDUCING ENVIRONMENTAL FOOTPRINT

Dematerialization, or achieving "more with less", was one of the principal tools in Fuller's design process, largely inspired by the lightweight structures found in the airplane, automobile and ship industry, which perfected minimization of use of material in order to reach better performances in the air, water or on the road.

Dymaxion House weighted only 2.700kg, excluding the bathrooms and closets (comparing to, as stated by R.B. Fuller, an average house of the same period that weighted some 150 tonnes) and could have been transported using a single truck carrying an 8.5 m3 cylinder. This is achieved by using the high strength materials such as steel and aluminium all of which have high environmental impact. The fact that balances the use of the energetically costly materials is the reduction in their quantity necessary to guarantee the desired performance.

In the Dymaxion House approximately 1751,6 kg of aluminium were used, for the following features:

TABLE 1. The weight of the aluminium elements in the Dymaxion (Wichita) House (Source: information provided by Henry Ford Museum)

Building Part	weight (kg)
Ventilator	186,6
Mast	5,3
Skin	360,8
Cage	207,0
Deck	1094,0
Foundation	6,8
Door	22,7
Bathroom	57,1
TOTAL	1751,6

The energy equivalent to the amount of aluminium used in the house is 367836 MJ, based on the assumption that the aluminium is not recycled, which would equivalent (if other materials were ignored and assuming the homogeneous structure of the walls, deck and roof) to the concrete shell of thickness of 29 cm or brickwork 27 cm thick (based on medium values of energy costs from [2]). In that sense the impact of the material, despite of its lightness remains high and unjustified. The calculus, however, changes completely if the material in question is recycled aluminium. In that case, the energy equivalent to the amount of aluminium used in the house would be 52548 MJ, (seven times less) which would imply a 4,1 cm concrete shell or 3,9 cm thick brickwork.

As seen here, the production of aluminium (first fusion or recycled) is decisive factor at the moment of considering the comparison of the energy costs between aluminium and other materials.

On the positive side, the lightness of the "building kit" implied the reduced impact related to the transportation: COx, NOx emissions, use of fossil fuels etc., as well as a reduced contact zone with the ground, which was disturbed only for the central mast foundations and anchorages. The assembly pieces themselves were light (none of them weighting more then 5kg) which provided for an easy, almost do-it-yourself assembly.

On the negative side, these radical reductions of the material weight lead to problems in the achievement of the interior comfort. Since the house was in an experimental stage still, no studies were done on the thermal insulation. The problems were reported also regarding the acoustical performance of the house that offered no amortization of the outside and inside sounds.

Therefore, in the case of Dymaxion House the dematerialization through the use of aluminium can be perceived as partially achieved, despite of the large ecological "backpack" of the aluminium itself, although with uncertainty about how would the interior comfort and other problems had been addressed in the further prototyping process.

6. DURABILITY OF ALUMINIUM IN THE DYMAXION HOUSE

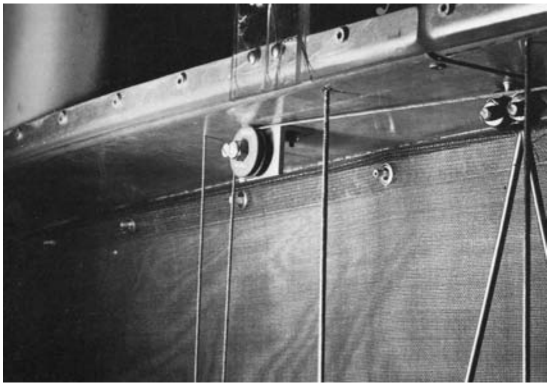
There has been an extensive study on the state of the aluminium after the Dymaxion House was disassembled in 1992 [7]. The aluminium used in the Dymaxion House was duraluminium, wrought aluminium copper alloys, corresponding to today's alloys 2014-T3 and 2024-T6.

The aluminium sheets in the Dymaxion house were protected by cladding layer with pure aluminium or aluminium alloy. It has been found that this protective material, in process of aging and after the forty six years of exposure to weather, merged with core material. The cooper from the core had passed to the cladding layer which therefore lost it protection against corrosion. Although different forms of corrosion were found in the house the majority of aluminium sheets showed only minor surface oxidation, while the material exposed to prolonged exposure to water suffered "localized surface corrosion" [7].

The study discovered that the points of attachment (holes for bolts and rivets) were especially vulnerable to the corrosion, since they permitted penetration of water to the core [7].

The form of the house and the vent on top provided the house with the structural stability even in

FIGURE 3. The aluminium (and other materials) was not painted thus simplifying the maintenance. (Source [5])



the case of tornados, which eliminated the need for repairs in case of natural disasters and provided the house with long durability.

In the case of Dymaxion, aluminium proved to be durable material whenever installed in the manner that avoided accumulation of the water or contact with other metals that leads to its corrosion.

7. DESIGN FEATURES: DESIGN FOR DISASSEMBLY

Having in mind that different layers of the building degrade on different pace, one of the key features for sustainable maintaining of a building is structural separation different layers, such as shell, partitions, installations, structure, etc. This facilitates preservation of functional parts when a repair or substitution is needed.

The Dymaxion House was designed with intention to conform an artefact that would be easily transported from one location to another. Therefore, disassembly was one of its main features. Structural and non structural elements of the house are separated. The structure consists of the following steel elements: vertical pole composed of seven tubes (4.8 meters long), tension cables and tubular rings that provide the shape, and aluminium profiles of the floor. The shell consists of: aluminium sheets, Plexiglas windows, and plywood floor deck placed on the 96 aluminium floor beams. For example the floor was assembled without any use of glue or nails—the boards are designed to fit together.

House's approx. 2000 parts were (at least in theory) designed to be mounted using screws and bolts, which would permit easy disassembly.

In addition, Fuller does not use composite materials but the pure ones, thus securing their easy recycling. The number of different kinds of materials is also limited, which adds the simplicity of the processing of the material after its useful life.

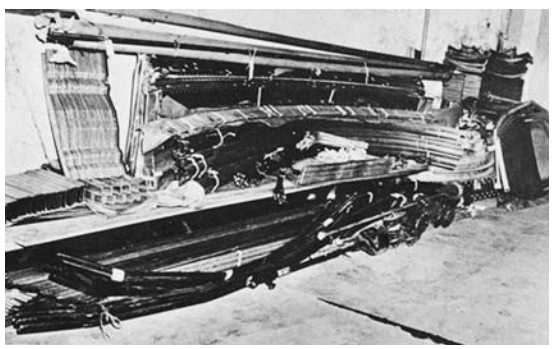
Apart form the sheets for external shell, aluminium is also used for the furniture.

In the present case, aluminium proved to be a material suitable for disassembly which is a basic step prior to the recycling, as well as for consecutive easy transportation.

8. GENERAL SYSTEM: HOUSING SERVICE INDUSTRY

Even if the aluminium is used in its pure state and not bound into composites or attached to other materials through welding or gluing, and designed for disassembly, its recycling is not guaranteed due to the unforeseen behaviour of the owners or deconstruction company in charge of dismantling and processing of the "construction waste". Therefore, an overall management system is needed in order that one or more parties assume responsibility for the post-user management of the building material, in this case aluminium. Fuller had in mind a broader system that, seen from the nowadays perspective has numerous environmental benefits. The scheme he was proposing was a service industry system, where buildings would have been rented to the individuals, but kept as a permanent reasonability of the manufacturer,

FIGURE 4. Assembly parts of the Wichita House. (Source [6])



that would maintain, repair, and even transport them in case that the owner decides to move to another place, and in the end of their useful life dismantle them, reusing the functional parts and recycling the unusable ones.

Experiences similar to this have started to appear in the last decades: one of emblematic examples is Interface Inc. company, that rents the carpet tiles instead of selling them, and keeps a permanent custody over its products, replacing them when and where necessary, while pursuing their final goal of 100% closed recycling loops and minimization of environmental impacts related to the production processes. The complexity of this quest is high, even if the product in question is apparently simple one.

The application of a similar concept to the house production, having in mind that a house is much more complex "artefact" composed of diverse materials with different lifecycles calls for a different system that could be organized though two different systems. One possibility is to start form one "type of industry" and to try to maximize the use of single material in a building ("all-wood", "all-brick" or in this case "all-aluminium" buildings, since this provides with an optimum control level over the lifecycle of the materials avoiding the complexity of the "artefact". The other option is to organize a system of service of general coordination and subcontracted service industries.

In the case of application of this system in Dymaxion House, it would be justified by small number of different materials used and by the assembly system that was applied.

Regarding aluminium, this would allow for its entire quantity, used in the building to be recycled and used again, which is favoured by the fact that aluminium does not loose its quality through successive recycling. The three characteristics previously stated; dematerialization, design for disassembling and durability would be one of the key factors for the organization of the here described service industry system.

9. CONCLUSIONS

Environmental impact of aluminium production, in this moment, is highly negative. In order to reduce the impact of this material on the long term, the use of aluminium should be oriented toward the products with long lifecycles which due to the minimization of the use of material through design (dematerialization) have minor environmental impact comparing to other materials.

The characteristics of the aluminium, such as lightness, strength, durability, lead to the use of this material for lightweight, transportable and demountable structures. When using recycled aluminium, the reduced quantity of materials needed for achievement of required performances can lead to the fact that overall embodied energy is similar or even smaller comparing to that of the energetically less intensive materials, due to the fact that the latter ones need to be used is bigger quantities.

The difference between the energy and environmental costs of first-fusion and recycled aluminium may be a decisive factor when deciding on aluminium use in a building.

The durability of the material, when properly designed makes it apt for the use in long life structures, as seen in the Dymaxion House.

The application of the pure materials without finishing and designed for disassembly is a prerequisite for the successful reparation, reuse and recycling.

The proper management of the material once the useful life stage is finished is one of the key issues when reducing the environmental impact of the material flows. The housing service industry, as proposed by the Fuller, offers a possible alternative for the contemporary make-and-sell system.

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