SUSTAINABLE BUILDING MATERIALS: LATEST PRODUCTION TECHNIQUES

Emanuela Manolova

Industrial zone, 2070 Pirdop, Bulgaria,
e-mail: e.manolova@aurubis.com

Abstract. Sustainable solutions lay the foundation for the brighter future of our planet. The construction industry consumes large amounts of materials and energy. Innovative solutions in construction can significantly affect the already established practices. Two directions can change the model – new materials and new methods of implementation. This article is focused on these aspects of construction which must be changed in order to achieve the goals of sustainable building materials production. There are many benefits of adapting sustainable materials: from healthier living – clean air and non-toxic environment, to safe natural resources from optimized sources, valorization of residues and application of recycled materials. Although the benefits are obvious, the transition is not a quick process. Construction regulations and standards lag behind ordinary building materials production and limit innovative ideas for a greener future. One of the possible solutions of this problem is to test the performance of the materials instead of limiting the amount of a particular material or component in certain compositions.

Keywords: sustainable building materials, Lean methods, Building Information Modelling (BIM).

1. INTRODUCTION

During the last decade, sustainability has become implemented in various aspects of human life. With respect to construction – sustainability combines different practices of creating a healthy environment based on the ecological principles of production of building materials and their extended durability. These ecological principles include aspects of the 3R concept (reduce, reuse and recycle). Some implementations of this concept include assessing the lifecycle of the building materials, conserving and protecting natural resources and creating non-toxic products which fulfil the requirements of the construction standards. The significant impact of the construction industry on the environment can be reduced using green technologies and Lean methods.

DOI: 10.7546/EngSci.LX.23.01.06

The lifecycle of construction materials can be divided into three phases: pre-building, building and post-building. This article is focused mostly on the pre-building phase, which describes sustainable material manufacturing in relation to the raw materials used for the process and reducing the energy needed for their production.

2. GREEN TECHNOLOGIES FOR BUILDING MATERIALS

Green technologies for production of building materials can vary depending on the raw materials used – natural, recycled or reused, and also depending on the innovative technologies for their production. This article emphasises the principle of using natural raw materials for production of artificial building materials, which is not sustainable anymore in the 21st century. Annual deposition rates of residues show that half of them are mineral processing wastes from several categories: waste rocks, mill tailings, coal refuse, wash slimes and spent oil shales. In the USA alone the annual mining and metallurgical residues are estimated to be 1.8 billion tons, with mineral waste accumulation of 50 billion tons for 50 years' period [1–2]. For the Republic of Bulgaria, the annual deposition rate of mineral waste compared to all types of waste is about 90%. One of the benefits of the European Green Deal, presented at the end of 2019, is production of "longer lasting products that can be repaired, recycled and re-used" [3]. In the context of production of building materials, it means that valorisation of mineral wastes is encouraged as a raw material for other production units. The need to limit deposition provides scientists and industries with new opportunities to use residues in new ways and in more industries.

2.1. Raw mineral materials for production of green building products

Mineral residues can be successfully used as raw materials in the production of green building products. They can be classified in several main categories: waste rocks, tailings, coal refuse, wash slimes and spent oil shale. All these mineral residues are produced as a result of complicated technological processes including hydro- and pyrometallurgical technology during extraction of ferrous and nonferrous metals, oil, gas and coal production. They have fine grain size, produced as a slurry, and are predominantly disposed under water for dust prevention, Fig. 1. Once deposited in a pond, they go through a dewatering process in order to become semi-solid or solid materials for further

Fig. 1. Pond for deposition of mineral residues, a potential source of raw material [5]

Fig. 2. Quarry for natural stone used as raw material [6]

utilization. Once excavated, they can become a source of raw materials for the construction process depending on their physical and chemical characteristics and the requirements of the standards. The world concrete industry alone utilizes 25 billion tons of products, 20 billion tons of raw materials, mostly with natural origin, Fig. 2, [4].

Residual materials can be successfully used as secondary cementitious materials in case certain pozzolanic activity is achieved or as a fine filler which is needed for better particle size distribution in the mix. Blended cements and concretes can be completely changed if mineral residues are added to their composition.

2.2. Energy used for green building products

The energy used for the production of natural raw materials can be significantly reduced by using mineral raw materials which have already been produced as a by-product of the extraction of other components. Most of the costs are related to dewatering those products compared to the extended production process of excavating, crushing and milling natural raw materials, Fig. 2.

2.2.1. Energy for production

The production process of green products combines different technologies to reduce the energy required for production using green energy and green technologies for CO_2 utilization. One of the options is using electricity from solar and wind sources for the production processes. According to the International Energy Agency about 26% of the world's energy nowadays is from renewable sources and it is expected to reach 30% in 2024. This also includes energy from hydro, tidal, geothermal and biomass sources. These energy sources are considered nondepletable.

Another innovative breakthrough technology uses CO_2 in the production process. According to Hepburn [7] about 3150 Gt of CO_2 are released on our planet annually and only about 21 Gt of CO_2 sink to the surface (both on land and in the oceans), Fig. 3. Nevertheless, the net atmospheric growth per year is 18 Gt according to data from 2019. It is possible to utilize the released CO_2 once it has been captured and, if stored properly, it can be used again in the production cycle.

There are several options for CO_2 utilization in concrete production – in the form of an aggregate injected during mixing or for CO_2 curing after the concrete has been cast. These processes turn CO_2 from a gas into a mineral and increase the strength of concrete thanks to the solid carbonates which are produced. As a result, the concrete requires less cement for hardening, which leads to a reduced amount of related emissions. According to the researchers from the University of Michigan, ready-mixed concrete can uptake about 3.8% of CO_2 and precast concrete about 9.6% of CO_2 from the total mass [8]. CO_2 capture can also be used directly to process other chemicals and materials, e. g., in iron ore filtration, steel slag carbonation, and red mud neutralization [9].

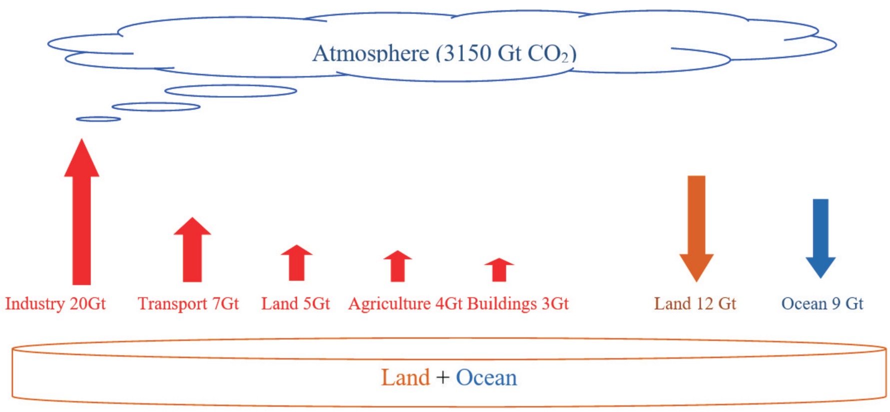

Fig. 3. Annual CO_2 sources and sinks around Earth's atmosphere [7]

2.2.2. Energy for delivery

The transportation of building materials, both raw materials and ready mixtures, once required a large quantity of energy. Due to the low cost of products compared to other goods, building materials are delivered over short distances. In most cases, production sites are close to the main source of the raw material (quarries, etc.) or located in the area of high consumption (big cities, industrial zones, etc.). The short distance means that refilling or rechanging the vehicles can be more flexible. New developments in this direction are related to fully electric trucks and cement trucks. One such innovation makes it possible to power the truck and the truck mixer body using a traction battery, eliminating the need for power electronic components. Electric trucks can reduce CO_2 emissions sufficiently. The next step is the production of renewable energy for the transport sector, which is one of the main pollutants. Software applications can improve the lifetime of the battery, coordinate several concrete trucks on a construction site at the same time, and calculate shorter routes to the final charging destination. All these algorithms are solved using Lean systems and Building Information Modelling (BIM) models.

3. LEAN CONSTRUCTION

3.1. Principles of the Lean methods

First described as a concept by Toyota to improve their production system and then expanded by Lean thinking, Lean methods are a business model

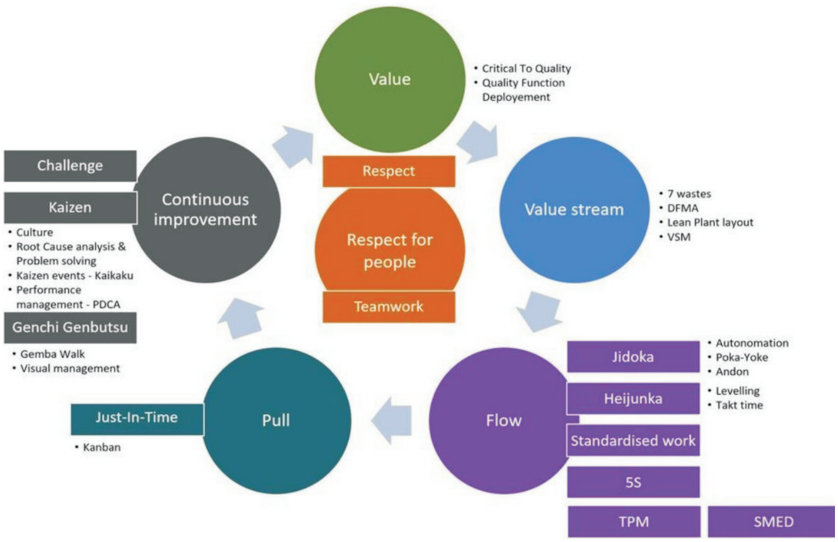

Fig. 4. Lean manufacturing managing model [11]

that makes continuous improvements in the operation and implementation of the processes, which guarantees optimum efficiency [10–11]. This is achieved by changing or removing ineffective practices, identifying and discontinuing unprofitable products and measuring and improving the productivity of the teams, Fig. 4. Sometimes it is easier to identify those areas that do not support growth, and remove them effectively.

The Lean model is divided into five different areas:

1. Description of the value: identifies the critical steps for best flows by measuring, controlling and prioritizing actions. The main steps combine – critical to quality characteristics (from customer's point of view) and quality functional development (from technical point of view). Value is the proper identification of customer's value by satisfying their needs with clear understanding. It also means that companies have spent their time, efforts and resources into working on a value-added product both for customers and for themselves.
2. Value stream map: includes activities required to design, produce and deliver a product to the customer, eliminating those that do not add value to the customer. The value stream map is more easily achieved by defining all the processes and steps that transform raw materials or ideas into working products that customers will use. There are four elements of manufacturing management: (i) The seven wastes; (ii) Design for manufacturing and assembly; (iii) Factory layout; and (iv) Value stream map. The goal is to surface all the steps in the process that do not add value to the final product and then work to eliminate those wastes.
3. Create a flow: continuous production without intermediate stocks or wastes in six principles: (i) Jidoka – stopping in case of fault; (ii) Heijunka – smoothing the process to compensate irregular orders; (iii) Standardized work – improves reproductivity and limits variations; (iv) The 5S method – preventing stoppages and malfunctions; (v) Single Minute Exchange of Dye Method – reducing tool, product and cleaning change times; (vi) Total Productive Maintenance approach – carry out as much as possible without stopping, and include all the factors that influence this.

   Creating a flow is the next logical step after eliminating the initially identified wastes in the value stream. Establishing a smooth flow means that the work is not impeded or blocked, quite the contrary – the product will flow smoothly toward the customer by creating value steps in tight sequences. Sometimes, a fluid flow is not as easy as it sounds. Introducing changes in the company causes resistant at some people and processes. Six principles support this transformation.

4. Establish a pull or so-called Kanban model: customer pulls the system, on request, upstream the system up to the last on the line by a continuous flow. Business no longer needs to build products, and only to store them as inventory. They were pushed by the customer once the customer required them.
5. Continuous improvement in three aspects: (i) Challenge – as a long-term vision; (ii) Kaizer – striving for innovation and evolution; (iii) Genchi Genbutsu – defining facts, correct decisions, building consensus, achieving goals, all at the best speed.

When a company goes through a Lean transformation, it realizes that it is not just a single project. Value identification, refinement of the value streams, establishing a smooth flow, and the constant efforts to ensure that you produce only when needed and in what amount, are all part of the continuous improvement initiative that the entire company must come together to support. This means that the Lean thinking must be embedded in the company's culture. The pursuit of the perfect product and process never ends. Therefore, the company must have a system in place that encourages everyone in the organization to strive towards improving their processes incrementally. This is where process improvement models like Kaizen come into play. Kaizen is a business philosophy to instill a culture of continuous improvement within the organization.

Last but not least, Lean methods are based on the concept of "respect for people or the people are at the heart of Lean manufacturing management". It requires an effort to understand others, respect them and establish relationships based on teamwork, stimulating growth through both individual and team performance. The Lean management principles can be transferred into construction using the so-called BIM, defined by Building SMART International as "a new approach to being able to describe and display the information required for the design, construction and operation of constructed facilities" [12]. The method can be applied in two directions: efficient design and optimization of the execution.

3.2. Lean methods in construction

First described as a concept for implementing Lean and BIM models in construction, it leads to a waste reduction in the execution of the construction planning process and therefore a reduction of the amount of material resources used, followed by efficient design and improved quality control, reduced costs for project construction works and decreased energy consumption, enhanced adaptivity to challenges and improved employee morale [13–14]. Construction wastes also related to delays, excessive transport, excessive motion and over processing are often detected throughout the process. Underestimating and underutilized people's talents, skills and knowledge is a sufficient deficit.

Lean construction methods can significantly improve construction process and production of building materials. The established practice in Bulgaria requires optimization, and Lean technologies seem to be a key factor for fast and efficient transformation of the sector. They can increase the work quality and on-time project completion by eliminating the wastes mentioned above. As a result, the worker satisfaction will increase, because they will have more control over the process. With respect to the production of building materials, the process can be modified by optimization of the raw materials deliveries, stocks and production, following the so-called Kanban model without excess of inventory, need for correction, over production, excess transport and excess motion. Long-term contracts with secured volumes can stabilize the process and make a smooth flow without excess stress and presence of mistakes. Quality control and regular internal inspections are also a necessity for adaptation of the Lean principles in Bulgarian construction practice. Better flexibility related to market demand is also a must. One of the main problems of the sector is the unstable quality of the produced building material, which significantly reduced durability and makes sales unpredictable. The latter is mostly

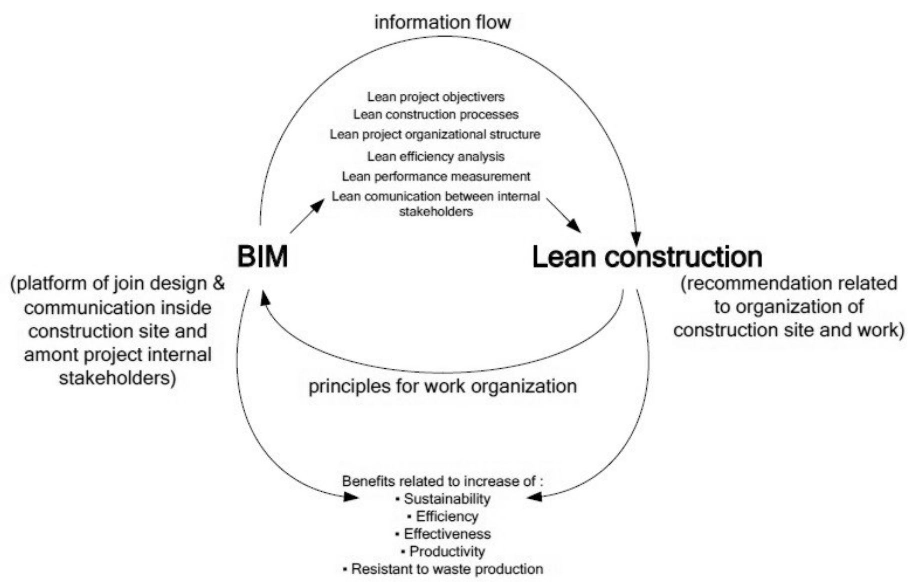

Fig. 5. The critical linking points of Lean construction and BIM [15]

valid for small production sites outside major cities. New production technologies and materials, including chemical admixtures and additives, are not yet common practice in these locations. Reducing CO_2 emissions and creating sustainable building materials are generally not well adopted.

In addition to the Lean technologies, the BIM models visualize the construction process through a common platform for design and communication between different stakeholders, Fig. 5.

The BIM model was identified as an essential technology for the efficient implementation of Lean models by project development, following six core principles of Lean construction: clients' values, value stream, waste accumulation, work process flow, pull scheduling and keep improving. Some brave specialists propose applying Virtual Reality (VR) and Augmented Reality (AR) and even link technologies to the blockchain concept [16–18]. The models can be related to prediction of the future by optimizing the management in construction companies by applying innovations in those areas that have been described as leaks. Further developments are expected in utilization of the energy and environmental analysis, constructive and structural analysis [19].

4. CONCLUSION

There is a need for an economic action plan and guidelines for the application of the concept of circular economy in the context of the production, use and recycling of building materials. The key factor is the carbon released in this process and the carbon capture in new production. Embodied carbon emissions for extraction, processing, manufacturing, transportation, distribution and disposition must be reduced in different ways: using fewer natural resources for building materials, reusing building materials, utilization of CO_2 in material production, creating materials with extended durability and minimizing waste during manufacturing. Standards should be adapted based on material characteristics rather than composition, which will extend the range of sources for their production. New optimization techniques such as Lean methods and BIM models should become part of the construction process. There is still a significant research gap in the area of Lean construction and BIM modelling. As the requirements that building materials must fulfil increase and environmental regulations change, Lean methods can transform the mindset by creating a culture built around innovation and efficiency.

REFERENCES

[1] R. J. Collins and S. K. Ciesielski, *Recycling and Use of Waste Materials and By-Products in Highway Construction, National Cooperative Highway Research Program, Synthesis of Highway Practice 199*, Transportation Research Board, Washington, DC, final report (1994).

[2] U. S. Environmental Protection Agency, *Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale*, Report No. EPA/530-SW-85-033, Washington, DC, December (1985).

[3] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (last visited June 20, 2020).

[4] E. Manolova and Ya. Ivanov, *Application of Construction and Demolition Waste and Other By-products in Construction*, Construction Materials for Sustainable Future (2007) 146–151.

[5] https://en.wikipedia.org/wiki/Tailings_dam (last visited June 20, 2020).

[6] https://www.crusherandparts.com/how-to-invest-in-a-quarry-aggregate-processing-plant/ (last visited June 20, 2020).

[7] C. Hepburn, E. Adlen, J. Beddington, E. Carter, S. Fuss, and N. Mac Dowell, The Technological and Economic Prospects for CO_2 Utilization and Removal, *Nature* (2019) **575** (7781) 87–97.

[8] L. Henrion, D. Zhang, V. C. Li, and V. Sick, *Bendable Concrete and Other CO_2-Infused Cement Mixes Could Dramatically Cut Global Emissions*, University of Michigan College of Engineering, The Conversation (2021).

[9] S. Valluri, *Carbon Capture and Utilization*, Dissertation Master's Theses, Michigan Technological University (2021).

[10] T. Ohno, *Toyota Production System Beyond Large-Scale Production* (1988).

[11] J. Womack and D. Jones, *Lean Thinking. Banish Waste and Create Wealth in Your Corporation* (2007).

[12] I. B. Kjartansdóttir, *et al.*, *Building Information Modelling – BIM*, Civil Engineering Faculty of Warsaw University of Technology, Warsaw (2017).

[13] M. Z. M. Zuhair, H. S. Jayasena, and M. Ariyachandra, Review on Lean Construction and TPS Approximation with BIM, in: The 5$^{\text{th}}$ World Construction Symposium 2016: Greening Environment, Eco Innovations & Entrepreneurship, Colombo, Sri Lanka, July 2016, pp. 399–407.

[14] B. Sertyesilisik and I. Kivircik, *Integrated BIM Usage in Construction Project Management, As a Way of Enhancing Sustainability and Lean Performance of Construction Industry,* Build. Inf. Model. Sharjah Bentham Sci. Publ. (2017) 204–223.

[15] A. Michaleski, E. Glodzinksi, and K. Bode, Lean Construction Management Techniques and BIM Technologies – Systematic Literature Review, *Procedia Computer Science* (2022) 1036–1043.

[16] P. Dallasega, A. Revolti, P. C. Sauer, F. Schulze, and E. Rauch, BIM, Augmented and Virtual Reality Empowering Lean Construction Management: A Project Simulation Game, *Procedia Manuf.* (2020) 49–54.

[17] C. Calderon-Hernandez and X. Brioso, Lean, BIM and Augmented Reality Applied in the Design and Construction Phase: A Literature Review, *Int. J. Innov. Manag. Technol.* (2018) **9** (1) 60–63.

[18] Z. Dakhli, Z. Lafhaj, and A. Mossman, The Potential of Blockchain in Building Construction, *Buildings* (2019) **9** (4), DOI: 10.3390/buildings9040077.

[19] R. Ahuja, A. Sawhney, and M. Arif, Driving Lean and Green Project Outcomes Using BIM: A Qualitative Comparative Analysis, *Int. J. Sustain. Built Environ.* (2017) **6** (1) 69–80.

Received February 10, 2023