Automating Design and Construction: The Emergence of "Offsite Manufacturing"

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In the last two decades, large portions of the USA and the European economy has been radically transformed by automation. However, the impacts of digitalization in the Design and Construction sector have been restricted to the use of software such as CAD, BIM or project management programs. These technological implementations have not radically transformed the way we build our environments.

The lack of productivity in the construction industry has had many impacts on our cities. Today the lack of affordable housing, labor shortages in construction, and an inability to respond with significant innovation to reduce emissions in a significant way are major themes in international discourses. In this article, we argue that to truly transform the construction industry we need to rethink the whole process of design and construction. In other words, it is not about improving current practices of design and construction but about envisioning machines that can design and build faster, cheaper, and greener.

In this article, we argue that since 2015 construction processes that are called "Offsite" have begun to emerge with significant traction. Offsite construction refers to processes that plan, design, manufacture and assemble elements of the construction of buildings away from the building site. Generally, "offsite" construction occurs in large industrial warehouses. In this method, the building sites become places in which crews mount quickly different construction elements that were created in warehouses far from the building location.

At the core of this paper, we examine how "offsite" construction will impact architectural thinking. We look at the work of enterprises such as NBBJ, Broad Group, Randex, Katerra, and BLOX. Architects in "offsite" manufacturing ventures are beginning to focus more on the variation of a particular program type and finding opportunities to produce standards that could guide a more rational manufacturing process while maintaining customization.

THE RISE OF "OFFSITE" CONSTRUCTION: MANUFACTURED CONSTRUCTION IN INDUSTRIAL WAREHOUSES

Offsite construction is not a new concept. It is associated with the tradition of prefabrication and modular construction that has a long history in the 20th century. Authors such as Gibb point to the beginnings of manufactured construction in the early 1850s that led firms like Eiffel to develop projects such as cast iron train stations and even churches around the world.[1]

But what is new today is the scale, number of start-ups, the new potentials of automation, and the large amounts of venture capital available. Today a large number of companies such as Katerra, Prescient, Broad Group, BLOX, Blu Homes, Project Frog, FullStack modular, Entekra, Randek, Lindbäcks Bygg, and many others are moving into prefabricating from flat elements to entire buildings. In this article, we compare the work of these start-ups to concepts such as "car platforms" in the automobile industry and strategies such as "chunking" in the airplane industry and how it will change the design and construction.

TYPES OF OFFSITE CONSTRUCTION

These new offsite enterprises are beginning to put forward completely new themes in the design and construction processes. From the point of view of constructability offsite manufacturing introduce new levels of system complexity,[2] new relationships and workflows between experts and organizations, and new differences that arise from building connections in the assembly of construction.[3,4,5] There are at least three basic types of offsite manufacturing today.

1. Temporary "Offsite" Facility: This takes place when construction organizations rent facilities close to the construction project to build a significant number of components of the project in a warehouse environment.
2. "Offsite" Element Prefabrication: In this mode, some construction elements are assembled in a factory led by a subcontractor or supplier. Examples include companies that provide elements that range from flat elements such as prefabricated walls to more sophisticated 3D volumes such as mechanical-electrical-plumbing (MEP) racks, bathroom pods, or entire prefabricated operating rooms. This mode is a hybrid that mixes the problems of management of on-site construction and the processes that arise from manufacturing. One of the most critical

Figure 1. Left image: pre-fabrication of the bathroom modules in the offsite warehouse for the Miami Valley Hospital project designed by NBBJ Architects. Right image: A modular bathroom unit being elevated to its floor in the Miami Valley Hospital project designed by NBBJ Architects (Image courtesy of NBBJ architects).

issues in element prefabrication is the connection or the decoupling point. The complexity of the connection can be reduced by standardization of the connection, communication, and method of construction.

3. "Offsite" Volume Manufacturing: This involves companies that manufacture the entire building volume in a plant and then just quickly assemble it on the site. These companies often cooperate with contactors who prepare the site and foundations for the project. A major theme for "offsite volume" manufacturers is the constant improvement of internal logistics such as the flow of materials, waste, and processes for improving lead time.

Below we offer case studies of the three types of offsite construction.

TEMPORARY "OFFSITE" FACILITY: NNBJ ARCHITECTS

One of the first examples of "offsite" construction in hospitals in the United States was led by the architecture firm NBBJ. The first project in which prefabrication was implemented by NBBJ was carried out at the Cardiac Center of the Miami Valley Hospital in Dayton, Ohio.[6] The main driver of the prefabrication, in this case, was not to prove that a building could be manufactured, but the aesthetic and functional aspects of the project that requires a high level of personalization for a particular health care client.

Once the hospital design was completed, NBBJ and the Skanska builder determined which system could be modularized. Five prefabrication initiatives were defined: 1. Unified external curtain wall; 2. Temporary pedestrian walkway completely pre-fabricated; 3. The manufacture of nurses' workstations in a modular and removable way; 4. The production of the patient room through the prefabrication of walls and bathrooms; and 5. An integrated rack system where all mechanical, electrical and plumbing (MEP) equipment is modulated above the corridors.

Initiatives 3, 4, and 5 described above were the most innovative. For this, the Skanka builder rented a warehouse approximately 5 kilometers from the construction site and pre-fabricated all those components "offsite." All the modular bathrooms, walls that made up the patients' rooms, and the 210 MEP racks (8 x 22 feet) were built in the warehouse. It took an 8-hour workday to transport and install 33 bathroom modules onsite and place a full floor of MEP racks on the site.

NBBJ participated in a second pre-fabricated "offsite" project at the Riverside Methodist Hospital in Columbus, Ohio. In this project, the entire team of architects, engineers, and contractors worked in the same office for 2 years. They developed the whole project in a single 3D BIM model and the contractor developed the construction sequencing models, 4D BIM, to plot the operation of the prefabricated warehouse, the production, storage and loading area of the components. In this second project, they assembled, delivered and installed the modular components with a "just in time" strategy which allowed for a very precise construction sequence between the warehouse and the construction site.

OFFSITE ELEMENT PREFABRICATION: PREFAB TIMBER CONSTRUCTION IN SWEDEN

Sweden has become a world leader in automated prefabricated offsite construction built in wood. Around 85% of detached single houses have prefabricated elements in Sweden, compare

Figure 2. Top images: The 30-story hotel called T30 was built by Broad Group in China in only 15 days. Bottom image: each truck transports 2 pre-fabricated modules of the hotel. Bottom image: each module includes the floor and all the vertical elements that go above the floor (Image courtesy of Broad Group, China).

it with about 5% in the U.S., U.K., and Australia. The Randek company is a major player in Swedish timber prefabrication.

Randek produce robotized assembly lines that transform the construction process similar to car manufacturing. Their production lines include systems that can be manual or fully automated manufacturing processes that aid the fabrication of walls, floors, and roofs. These systems range from butterfly tables, gigantic beds to produce roof truss systems to specialized machinery that allow the automatic application of stucco, the assembly of window frames, the semi-automatic production of roof boards or equipment for beam insulating.

One of the leading home manufacturers in Sweden is Lindbäcks Bygg and they use Randek technology. In the assembly lines of Lindbäcks factory, there are no carpenters with tape measurements or hammers searching for drawings, it is all is highly automated. In the production floor of Lindbäcks there are no framing boards, wood is supplied into manufacturing lines that align and fasten the framing to any type of form. A wall can be produced in about 15-17 minutes with windows, doors, and insulation.

After they completed a new manufacturing facility in 2017 they are aiming to complete 2,400 apartments per year. Still the assembly and finishing of the pre-fabricated volume still require hand labor. Swedish companies such as Lindbäcks Bygg, Derome Bygg, Stora Enso, and many others are investing heavily to increase the capacity of offsite construction in larger building types. In particular these companies are looking at new techniques such as cross-laminated timber (CLT) that is a solid wood panel product that is lightweight but has a higher load capacity. CLT makes possible to build taller wood building. Going larger with timber structures is the next step for offsite companies.

More than 85% of single houses have wood prefab elements in Sweden. An interesting lesson for contemporary architecture is that the Swedish experience in automation has not produced repetitive mass-produced buildings. Particularly in single houses, one can see a big variety of architectural designs. Similarly, a noticeable quality in design is beginning to occur in multi-story wood apartments.

OFFSITE VOLUME MANUFACTURING: BROAD GROUP, CHINA

In China, the Broad Group Company has astonished the prefabrication and modular construction category by completing several buildings in record time. In 2012 and 2013 they built several structures, including a 30-story hotel that was built in 15 days, and a 57-story skyscraper in just 19 days.

For Broad Group, prefabrication is much more than a quick construction. It is an effort to produce more sustainable buildings that use less material, weigh less, use less energy, assemble quickly on the site, be more secure for the construction workers and be significantly cheaper.[7] To achieve this they had to rethink the entire load-bearing structure and how the building was manufactured in offsite factories and quickly assembled onsite.

One example is the T30, a 30-story high hotel with 330 rooms and 65 parking spaces, that was built in 15 days (this time does not include the construction time of the concrete foundations). The T30 was made of several prefabricated modular components (the steel frame unit measures 51’ 2” by 12’ 6” with a depth of 1’ 6”) that were moved from the manufacturing plant to the construction site using trucks. Each truck transported 1,200 sq. ft. of prefabricated floor modules. The floor unit incorporates everything from water pipes and electrical systems to ventilation shafts, ceiling lights, cables, floors, and bathrooms. Other components produced in the factory are vertically braced columns, interior walls, and all façade modules. Once several floors and vertical elements are screwed into place, the components of the prefabricated facade system are placed to wrap the building.[8]

No welding or water was used at the construction site. There was no injury incident, and there was only 1% of the waste compared to traditional construction. According to the senior vice president of Broad Group, Mrs. Juliet Jiang, 93% of the T30 was prefabricated “offsite” in 45 days in its factory and at a cost of about US$ 100 per sq. ft. Mrs. Jiang projected that in

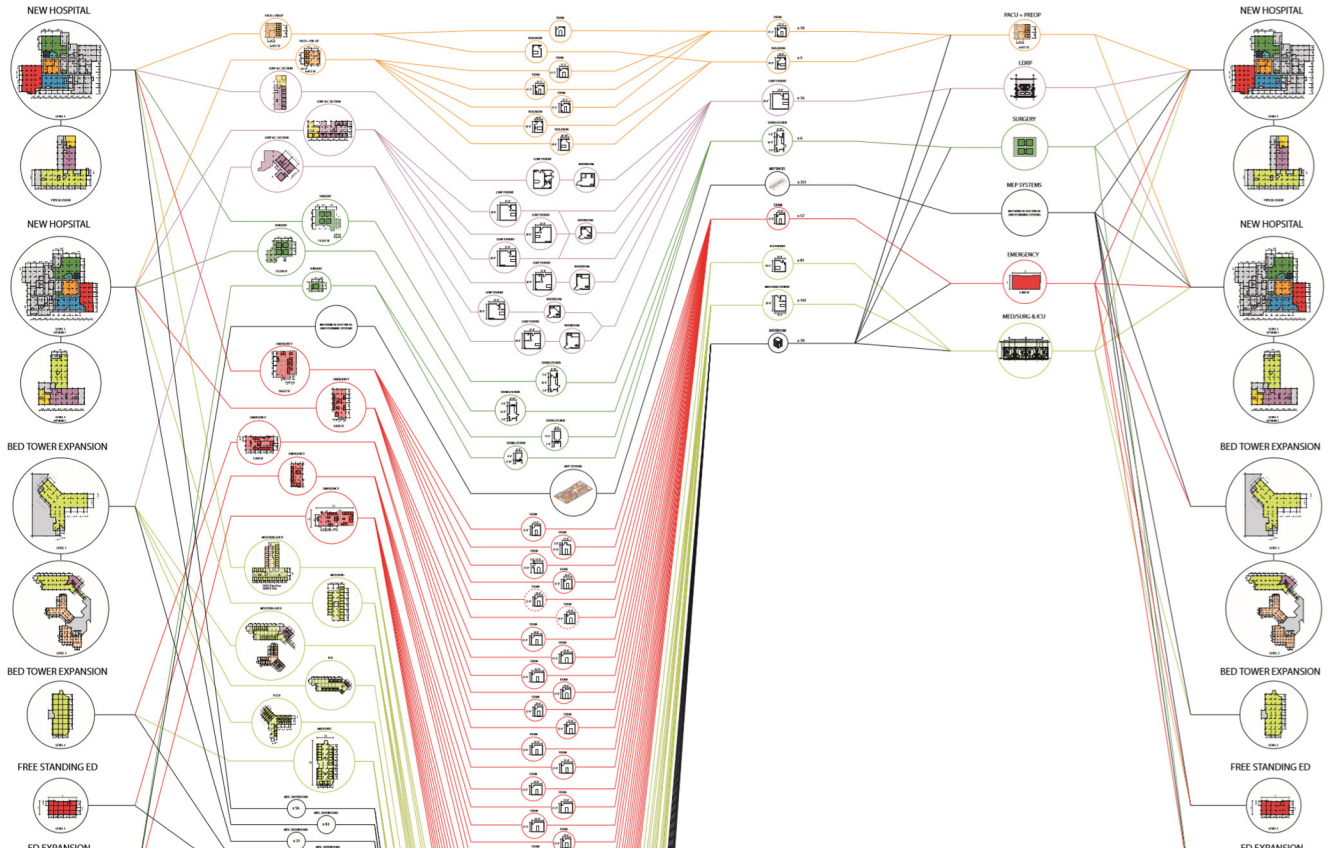

Figure 3. Mapping of the program analysis that BLOX developed for a health care client. The architects studied how each department and program was designed at the various hospitals owned by the client. Even though the client had design guidelines, they discovered that there were many design variations of every single program. In order to develop future guidelines for offsite construction, they reduced the variation into 9 manufactured modules. On the right side of the map above are the parts they developed to prefabricate bathrooms and MEP racks (Image courtesy of BLOX).

the future a building similar to the T30 could be prefabricated in only 7 days and at half the cost.[9]

OFFSITE VOLUME MANUFACTURING: KATERRA

Katerra was established in 2015 in Menlo Park, California, USA. In just 3 years this company already has more than 1,500 employees in the United States and $3.7 billion in new construction project bookings worldwide after they merged with Indian company KEF infrastructure in June 2018. Katerra seeks to optimize the design and construction process by combining BIM with modular manufactured construction. The company has a standard kit of building components and products for the interior from which designers and customers can choose. Katerra factories are set up to produce these parts more precisely, economically, and more rapidly than can be produced by workers in a traditional building site. The works are prefabricated in segments, for example, walls include doors and windows and ready to be dispatched. All parts are identified with Radio-Frequency Identification (RFID).

These RFID tags are connected to information that allows seeing how the components should be manufactured, transported and assembled on the site. This information also allows local inspectors on the site to examine the construction. Katerra's pre-fabricated systems and products arrive on-site with just-in-time delivery transforming the construction site into a place where the different parts are assembled.

The construction industry is a lagging industry in technology and is often organized around projects. As a sector, it invests little in research and development, and Katerra affirms that less than 1% is invested in new technology. Katerra today is learning how to develop patented technology to further facilitate the process from design, acquisition, and assembly. They are also acquiring construction and architectural companies and building several new factories. Katerra was co-founded by Michael Marks, who is a serial entrepreneur, he was the CEO and president of Flextronics International Ltd., one of the largest electronic manufacturing companies in the world and was briefly the CEO of Tesla Motors in its infancy.

Katerra's senior team comes from the world of electronics and investment banking. This is a typical story of how other industries have been revolutionized by entrepreneurs who come from the electronics industry. The most radical changes

Figure 4. View of the offsite manufacturing plant at BLOX in Bessemer, Alabama (Images courtesy of BLOX).

generally do not come from within the industry itself. For example, Amazon, Uber, Airbnb, and Facebook did not emerge from their respective sectors such as retail, taxis, hotels or the media, but they were guided by people from outside those industries.

MANUFACTURING PLATFORMS

One of the big challenges of manufacturing construction is to balance customization and standardization. A big lesson can be found in car manufacturing. Most car manufacturers do not design and build a car from scratch. Most vehicles are built using similar "car platforms." "Car platforms" have shared parts such as chassis, tools, and production processes across models and brands.

For example, today is standard practice that different models of brands such Renault and Nissan use similar chassis and components which helps to reduce development and production costs, easier inventory management, increased quality and shared innovation.

ARCHITECTURAL THINKING FOR OFFSITE MANUFACTURING: THE CASE OF BLOX

How can we translate the lessons from design and car manufacturing to construction? What are the impacts of "Offsite" manufacturing in architectural thinking? Chris Giattina is an Architect that founded Giattina Aycock Architecture Studio in 1985 in Alabama. In the 2000s he was designing training facilities for Honda and Kia which introduced him to manufacturing methods that are used by car manufacturers. In 2010 he founded BLOX, an offsite construction company dedicated to design and manufacture medical building components, today BLOX has a 250,000-square-foot manufacturing space in Bessemer, Alabama, and is one of the leaders in the USA in manufacturing entire walls, rooms, and buildings for health care clients.

Giattina says that with offsite manufacturing architects need to focus more on the program, the parts that make a building. He believes architects need to find means to analyze the variation of a particular program. Giattina says: "we need a fundamental mind shift and needs to start by first understanding what the program is (e.g., Marriott's worldwide hotel program). Once we understand the program, we need to learn and detect how to remove unnecessary variation. And finally, once unnecessary variation is removed from the program, we can begin to standardize. Then we can create interchangeable parts, which allows us to build a supply chain that can work at many different levels efficiently."[10]

Giattina began to develop his design-manufacturing thinking in the work he did for Hospital Corporation of America (HCA). HCA has more than 250 hospitals in 20 U.S. states and the United Kingdom. HCA had robust design standards but in every hospital, the program was reinterpreted in different ways. Giattina and his team began to map the configuration of each program (such as patient rooms, exam room, surgery room, bathroom, etc.) inside each hospital and they discovered a series of patterns of non-standard modules.

The next step was to remove unnecessary variation and standardize parts. Once standardization is understood they were able to design and manufacture (for example standard bathrooms, headwalls, or MEP racks) in a way that can be interchanged in different projects and can go through different regulatory health-care bodies in different states.

THE FIRST STEPS OF OFFSITE

Currently, BLOX has a manual assembly line. Giattina is critical and thinks that BLOX is manufacturing the way we used to manually produce planes during World War II. He dreams to move the process of building manufacturing to how Boeing today makes its 787 planes. Boeing manufactures its 787 planes by "chunking" it around 50 parts. Each part is assembled by a different manufacturer, for example the front fuselage is

assembled in Kansas, the center fuselage in Italy, the wings in Japan and the wingtips in Korea.

Boeing just brings all these pre-assembled parts together in their gigantic warehouses. Boeing reduces the development time and costs by outsourcing 70% of the development and production to around 50 suppliers which are world experts in producing these pre-assembled aircraft parts. A more advanced manufacturing vision for the design and construction industry will involve a dramatic shift in the supply chain. An ecology of suppliers could compete for particular pre-assembled building parts. With time major suppliers could invest in research and development that will improve their processes explosively.

OFFSITE: STANDARDIZATION AND CUSTOMIZATION

In standardization, there must be variations because in architecture there are different sites, markets, clients and special conditions that make each project unique. In order to advance ideas of variation and standardization BLOX has designed chassis modules. These chassis are a 15'x15'x60' module that can be deployed to many parts of the program in a hospital such as a CT module, X-Ray, central plant, room, Lab module, or a patient room. Most of these parts are delivered to the job site as flat parts or volumetric parts.

The speed of design and construction are critical aspects. In one of the projects that BLOX completed the construction price has come at 20% below cost. However if one monetizes the speed of design and construction and includes the cost of using the facility before it would be completed with traditional on-site construction then the total price goes down to 40%. Part of the workforce of BLOX is fully dedicated to developing digital tools to fully automate the kit of parts. This will further improve the speed and control of the manufacturing and assembly of the project.

CONCLUSION

It is expected that by the year 2023 around 6% of all construction in the US will be "offsite." At this trend, it is feasible that by 2035 more than 50% of all new construction in the US and Europe will have significant "offsite" construction components. We argue that although today's "offsite" construction is highly manual, both in design and manufacturing plants, we will see a clear trend in the development of semi-automated design processes based on manufacturing construction systems that will have more automated assembly lines. This will lead to building entire prefabricated elements while maintaining a significant number of architectural customization.

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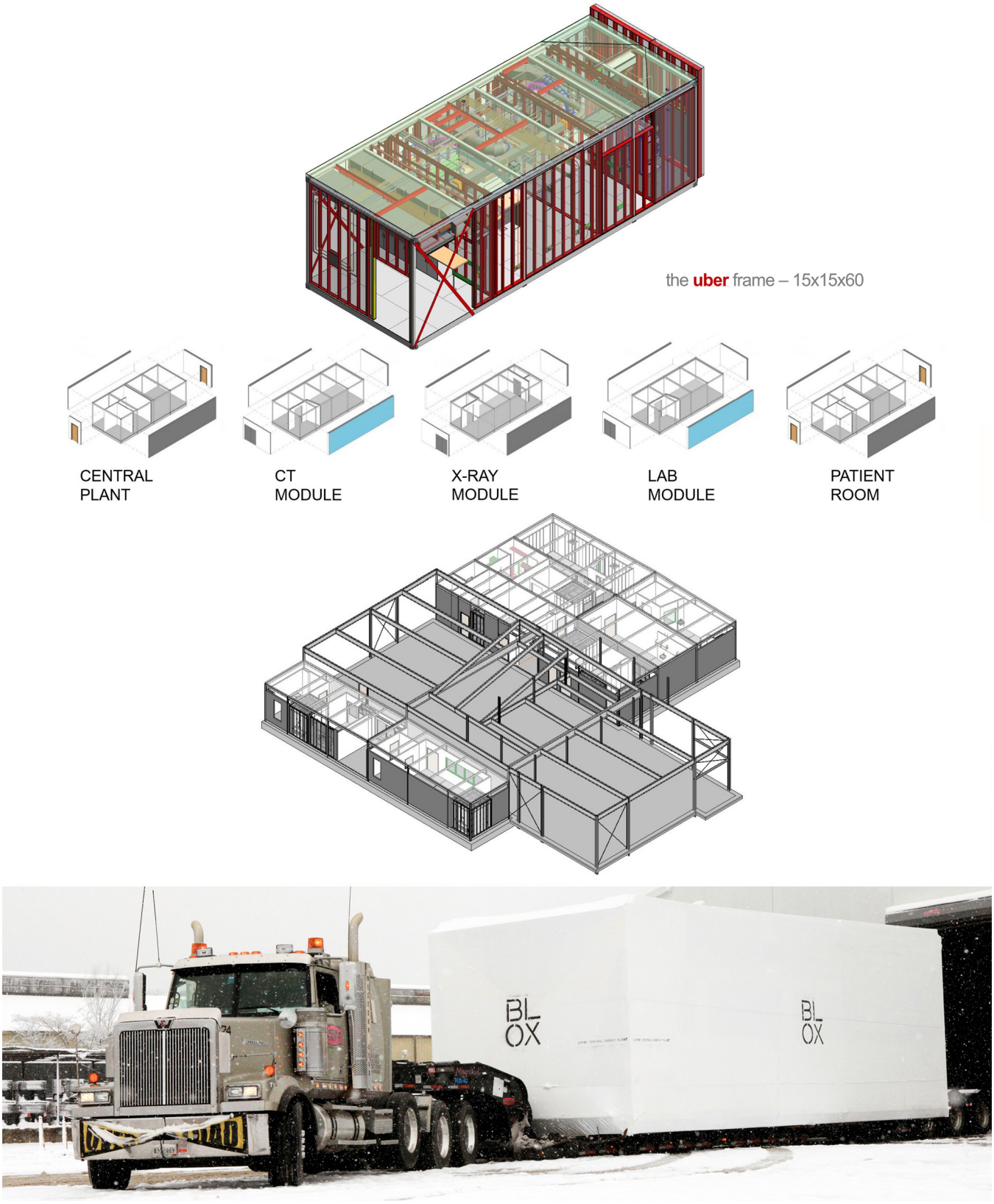

Figure 5. Top images: A single “manufactured chassis” of 15’x15’x60’ called “UBER” (first image) can host a series of programs for a healthcare facility (second image) that was built in 14 weeks (third image). Bottom image: A prefab module of 15’x15’x60’ manufactured by BLOX is transported to the job site (Images courtesy of BLOX).