



Technical Research Paper

# Project A.H.E.A.D

- Affordable Housing Enabled by Automation-oriented Design

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## Abstract

*How to use automation-oriented design to provide an affordable, customizable and efficient solution for the increasing demand of housing in Bandung and alike emerging cities in developing countries*

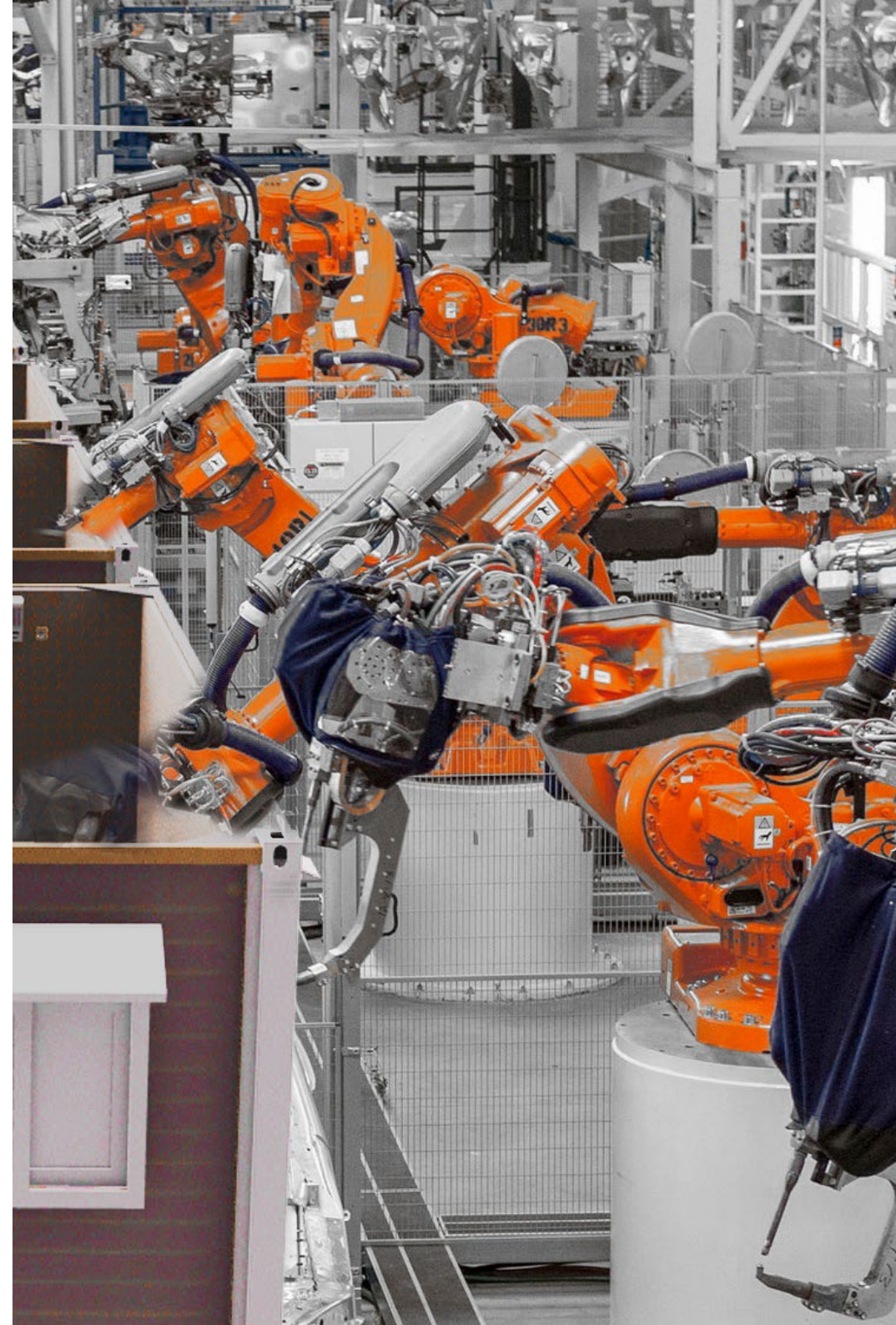
This paper tries to provide a background of knowledge to support answering the question.

In order to try to fill the gap between housing demand and provision in emerging cities in developing countries, the research tries to study the possibility to transfer automation/robotics technology, which has been greatly improving efficiency and productivity in most manufacturing industries, into construction and architectural design.

After introducing the background, this paper is then split into two parts. The first part focuses on the requirements of housing product. The needed amount of housing unit, housing space arrangement, affordability issues, and typical site condition are analyzed. The second part focuses on how to use the technology of automation/robotics in construction and design. Different types of robots, modularity and design principles generic for construction automation are discussed, with referencing products/projects, and each is discussed considering suitability in correlation with the requirements of the housing product.

### Keywords

Affordable housing, automation, robotics, construction, automation-oriented design, robot-oriented design



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# Introduction

## The problem: informal housing, urban Kampung

The Indonesian city, Bandung, has been facing a serious housing problem. Bandung is the third largest city in Indonesia by population. There are 2,550,000 in the city, 8,600,000 in the sprawling metropolitan area, and immigrants are still flowing into the city at a high rate (UN Habitat, 2015). The city is growing fast. It is a center for tourism, manufacturing, textile/apparel, education institutions, technology, retail, services, plantation/agriculture, finance, pharmaceutical, food, etc. However, the supply for housing, especially affordable housing for people with middle to low income is far from enough.

The locals have turned to a self-helping solution for this situation. Because of limited finance and resources, lots of the citizens chose to build their own homes with makeshift building materials and with very limited standards and technical support, and often lack organization and intervention of the government or social organizer. The areas where these self-help housing are densely built are often referred to as urban kampungs (Tunas & Darmoyono, 2014). The building and environmental conditions are often quite undesirable. There are several main characteristics of kampung (Figure 1), according to Tunas and Darmoyono.

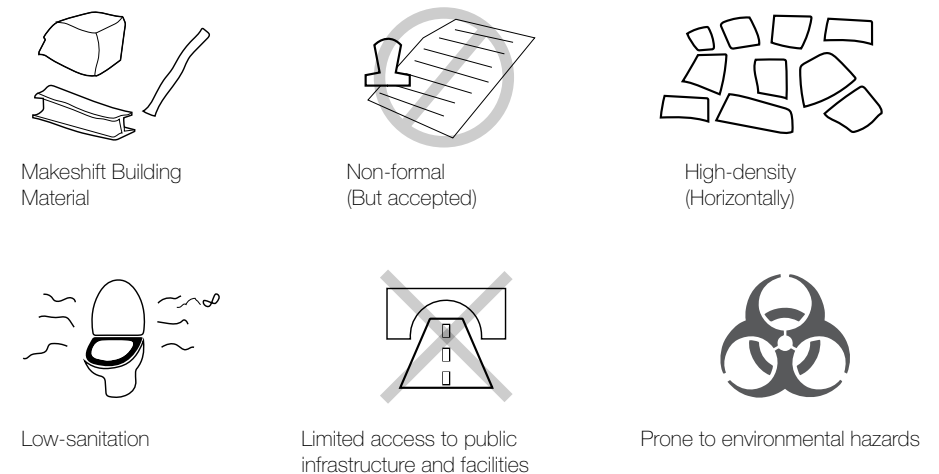


Figure 1. Characteristics of Kampung (Tunas & Darmoyono, 2014), own drawing based on the article's content



## The larger background: the gap between supply and demand of affordable housing

The situation in the kampungs is in fact a result of a larger social problem, which is the increasing demand and the lack of affordable housing supply in Indonesia and many developing countries alike.

The demand is driven by the rapid growth of urban population, due to immigration, urbanization and natural growth. During the period from 1990 to 2014, the urban population in Asian urban has increased from approximately 1 billion million to 2 billion. And this population is estimated to be 3.3 in 2050. Indonesia is no exception. Its population has grown from 55 million in 1990 to 134 million in 2014, and is expected to be 228 million in 2050. The annual change rate of Indonesia is 1.5, while the world average is 0.9 (UN Department of Economic and Social Affairs, 2014).

This has resulted in the huge demand on housing, especially affordable housing for the large middle to low income population group. It was estimated in 2005 that the total amount of annual new housing unit needed in Indonesia is 735,000 unit, with an additional 420,000 in need of improvement (UN Habitat, 2005). In a recent news, it was said that the amounted gap has been 13.5 million units in 2014 (Antara News, 2015).

However, this demand has far not been met by the formal sector, which includes both the government and the market. The government does not have enough finance for construction of housing units and claiming lands. The market, on the other hand, only meet the housing needs of the top income group of the

population (Ferguson, Smets, & Mason, 2014). In Indonesia, the first national public housing program, PERUMNAS, has only fulfilled a very small part of the demand. Since its establishment in 1974, it has only built 500,000 housing units so far, which does not even meet the demand in a single year (PERUMNAS, 2015). The amount housing products PERUMNAS has produced from 2008 to 2012 is listed in appendix a.4. So far, informal housing, including self-help housing in kampungs, has been the major source of supply in Indonesia.

### Housing Provision

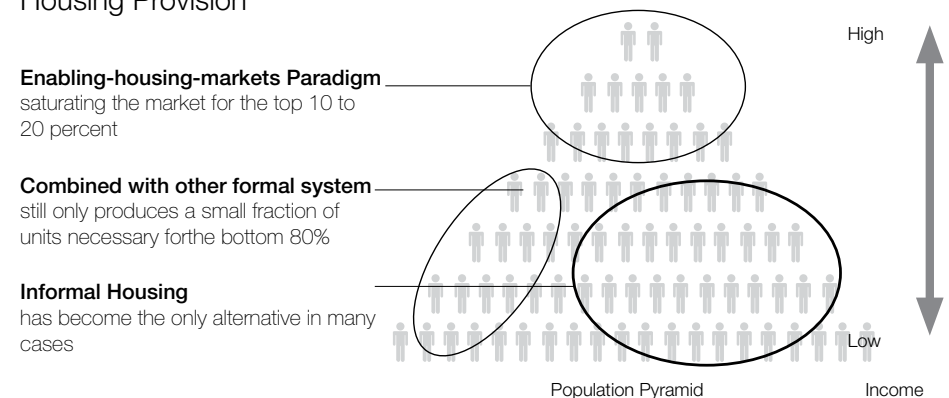


Figure 2. Housing provision (Ferguson, Smets, & Mason, 2014), own drawing, based on the content of the article

## The limitations of Self-help housing

While it has been an indispensable part of the housing supply in Bandung and other Indonesian cities so far, and it is true that many kampung improvement programs have made some major achievements, self-help housing might not be the ultimate solution for affordable housing.

The limitations of self-help housing could not be ignored (Figure 3). There are several major limitations (Bredonoord & Lindert, 2014). First, though being extremely dense in horizontal arrangement, self-help housing often fail to achieve density in the vertical direction, due to limited technical support and resources in design and construction. Density is the key to a more sustainable housing and urban planning, and with self-help housing alone this can be hardly achieved. Second, construction rate of self-help housing is quite limited, and is difficult to really meet the increasing housing demand. Thirdly, without sufficient professional support, self-built houses often have very low technical quality. This does not endanger people who live in the house, but it is also dangerous during construction period.

According to Bredonoord & Lindert (2014), self-help housing needs assistance. It is suggested that technical training be offered to self-builders, and with additional education and consulting. However, such training, education and support is difficult to be offer to large groups of people. It is often more efficient that specialized organization or enterprise manage the housing products, though in the current market most are only concerned with top part of the population pyramid. This situation needs to be changed



Figure 3. Limitations of Self-help Housing (Bredonoord & Lindert, 2014), own drawing, based on the content of the article



## Massive opportunities for affordable housing developers

Indonesia is the world's fourth largest countries by population and home to about 250 million people. As is mentioned, in Indonesia there is currently a huge backlog – 13.5 million, or even 15 or 16 million according to other sources – of housing units needed, and each year there is new demand of 735,000 or 800,000 housing units. With urgent need and shortage of supply, while on one hand constructing thousands of new homes by government institutes, on the other, the government of Indonesia has launched a series of programs and policies, including subsidizing mortgages for low-cost properties, to support the provision of housing, especially affordable housing for the low-end market, which provides massive opportunities for housing developers (Global Business Guide, 2016).

While the cost of conventional building keeps rising due to increasing cost in labor and resources, modular housing seems to gain increasing attention because of its advantages in productivity and cost control (Global Business Guide, 2016). However, in addition to that, the author tries propose a more progressive or even “radical” – as in many cases it may sound- solution, which is automation/robotics in construction.

## A potential solution: automation/robotics in housing construction

Since the last robotic boom in the 1970s, the manufacturing industries have been utilizing automation/robotics technologies in production. Through these years, automation/robotics combined with CAD (computer aid design) and CIM (computer integrated manufacturing), has been greatly increasing the productivity and efficiency of these industries. As for the construction, though being an industries that has a long age and had been most advanced in many periods in human history, it has been the least familiar one with automation/robotics technologies until very recently (Balaguer & Abderrahim, 2008).

For most industries, productivity (output/input in terms of finance) and efficiency (resources consumption rate) are the key factors for success. As a currently labor intensive industry, the construction industry rates very low in these two aspects (Moselhi & Khan, 2012), whereas the general manufacturing industry has improved tremendously (Bock & Linner, 2015). As labor price rising and production speed stagnating, the productivity in construction industry in Japan falls far behind average (appendix a.1). Another example in Europe, productivity in construction is stagnating since 1993 while the automobile industry rocketed in the same year (Balaguer & Abderrahim, 2008). As for efficiency, without efficient management throughout the construction cycle, material consumption rate also goes relatively much higher than other industries in the US (appendix a.2). It can be expected that the implementation of automation/robotics technology in construction will make significant changes by increasing productivity and efficiency.

Another advantage this technology provides is the possibility for mass customization, offered by its re-programmability and flexibility. To cater to various sizes and shapes of the construction plot, design and products needs to be adapted accordingly, and this would significantly increase resources cost. To be able to be customizable at lower cost would make a huge difference for the product to be offered. An example is that automobile manufacturers nowadays would often reprogram their robots for another car model. For instance, in 2011 BMW reprogrammed 120 assembly robots originally for Z4 to build their new X3 (Jouret, 2011).

The production and consumption of housing products is deeply correlated with four fundamental elements in construction process: land, finance, construction skills and building material (Smets, Lindert, & Bredenoord, 2014). An evolution in construction skills could play an important role in solving the gap between supply and demand. What exactly would be this need, and how can we meet that need with affordable housing products developed using automation/robotics technology, these questions are what the rest of this paper is going to answer.



## Research Methods

The paper mainly discuss about two aspects: the first is the requirements for the housing products (typology, affordability, and possible customization), and the second focuses on the knowledge to meet these requirements with automation/robotics technology.

The requirement research is done through literature study and data analysis. The typology study is basically a summary of results done by previous researchers and students. Affordability is researched through investigating the statistics provided by the United Nations, the World Bank, and Indonesian government through BPS (Badan Pusat Statistik), and making assumption based on these statics and common theories on affordability. However, though customizaiton would of course be a needed requirement, it is deemed to be part of the typology study, because the objective of customization is to provide personalizable housing product that can adapt to various sizes and types.

For the automation/robotics technology, the research is done mainly through literature. The sources are articles (Balaguer C. , et al., 2002; Howe, 2000; Leyh, 1995) and books (Balaguer & Abderrahim, Robotics and Automatoin in Construction, 2008; Bock & Linner, Robot-Oriented Design, 2015; Nof, 1999) etc. Based on the sources, three main aspects of information (robotics, modularity, and design principles) that is essential to the topic is collected and summarized.

To further link the technology to the specific need in Indonesia, in each chapter

the products, types, and methods are analyzed with consideration of the specific context when it is feasible. What kind of robotics would be suitable to carry out the construction job, considering the site condition in Indonesia? What kind of modularity would be suitable to meet the needs of various typologies while being feasible to be operated with robotics on the construction site? And what kind of principles would need more attention in order to better meet these requirements? General information is first studied to provide a background for discussion, and it would be discussed on the basis of specific situation.

After the study and analysis, reference projects are analyzed with regard to the mentioned 3 aspects. This part tries to provide information from existing built projects' angle to further study what types of robots, modularity, and design principles are suitable for producing housing products for Indonesia.

# Part 1: The requirements of housing product

This part mainly answers the following 2 questions: what kind of dwelling space is needed (and also the sizes), how to price the housing product to make it affordable for the target group. Customization is of course a requirement, but since the objective of customization is to provide products that can adapt to various need of space compositions and sizes, it is not independently studied here.

## 1.1 Typology of current kampung house

In order to be able to meet local customer needs, the typology of local living space are studied before designing the housing product. The following paragraphs mainly summarize the results of previous researches (Funo, Yamamoto, & Silas, 2002; Funo, Ferianto, & Yamada, 2005).

### 1.1.1 Direction, roof, & volume

The first characteristic should be noticed is the direction of house. Most houses face the street with their gable side (but not necessarily). This is because the width of house is usually limited, and the depth is often much longer than width, by which way higher density is achieved on the horizontal level (Figure 1.1). However, the width could still vary in a range, based on the wealth and site the owners have. According to a survey done in Kedung Doro area, the

width of the frontage range from 3000mm to 6000mm.

The types of heading are mainly the following three: 1, gable-roof, often with their gable end to the road, or in some other cases, with the ridges parallel to the road; 2, flat-roof; 3, hipped-roof, which is usually seen in large houses, but still often face their narrow side to the road. The volume of houses vary from single, double, and multi-storey. While gable-roof and hipped-roof often use corrugated asbestos sheet for cladding, concrete roof often appears in double and multi-story houses.

The main axis of a house, however, is often parallel to the long edge of the house, no matter which side it use to face the road or how the roof is directed. Along this main axis, different spatial units are arranged (types of spatial units will be discussed later). A composition of a series of these units becomes a basic dwelling unit, based on which further combination or extension can be applied.

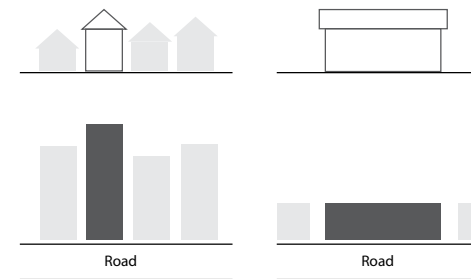


Figure 1.1. Two ways of horizontal organization, own drawing



### 1.1.2 Basic dwelling unit

A basic dwelling unit can consists of following spatial units: 1, t-terrace; 2, L-living room, or guest room (ruang tamu); 3, b-bedroom (kamar tidur); 4, d-dining room (ruang makan); 5, k-kitchen (dapur); 6, WC-bathroom (kamar mandi). Based on the condition or the intended use of the dwelling unit, the composition can vary. There are 5 basic types according to Shuji Funo's research (2005) (Figure 1.2).

From type A to E, as the complexity increases, the other spatial units including WC, kitchen, and dining room are added to the core units: living room, bedroom and terrace.

Type A is mostly for rental use for singles. The width is approximately 3m, and the depth varies around 4m. Since there is no WC and kitchen, the tenant needs to use public WC service in the kampung and have their meals in other places. Type B is an upgraded version of type A, with an addition WC and 4 to 6m depth. Type C is a further variation, the depth needs to be even larger. Type D is a very popular one, with solid wall partition between living room and bedroom, and the depth could range approximately from 7m to 9m. Type E can be understood as a single dwelling unit, or an upgrade with several side rooms based on the main living room core.

According to Indonesian's recent building regulations, 36 m<sup>2</sup> is the minimum acceptable space for one dwelling unit to receive subsidy, because housing smaller than this is considered "unhealthy". However, a typical Type D house

may only be 3m x 7m, which is 21 m<sup>2</sup>. If the housing product is to comply with the new regulations, it should be designed to be around 36 m<sup>2</sup> and probably have a similar articulation of space with Type E.

However, these types are not stereotypes. They represents a pattern which shows how spatial units may be added to the core spaces. All the articulation, sizes, and be varied. What is important here is the elements that exist and the spatial sequence they tend to follow, but not the exact way they are arranged.

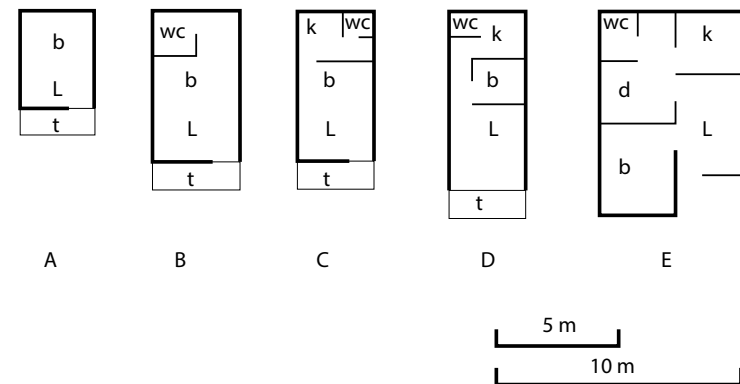


Figure 1.2. Five types of basic dwelling unit, redrawn by the author on the basis of Funo's research(2005)

### 1.1.3 Progression of house

In kampung, a house is usually not fully predetermined, but extended with additional construction overtime. A house can be extended in either horizontal or vertical direction. In horizontal direction, not only can it be extended with side rooms (as shown by Type E), but also along the main axis, which resembles the transition from type A to type D. The right shows two examples of extension (Figure 1.3).

Besides the various possible forms of structural and spatial transformation, the reason for change and the use of spaces could also be multiple. Adding more rooms can either be providing rooms for offspring, or leasing the room to guests to earn more income, or simply because the owner have eventually enough money to build it. In some cases, the living room could be transformed to a store, which has relatively high commercial value since it faces directly to the road, and the room behind it would take its place.

The organization and use of space, and extension of structure is very flexible. This raise a challenge for the product design. In what way, by using what kind of modularity and robotic construction method, could it be more feasible to be adapted and extended, is a question the product needs to answer.

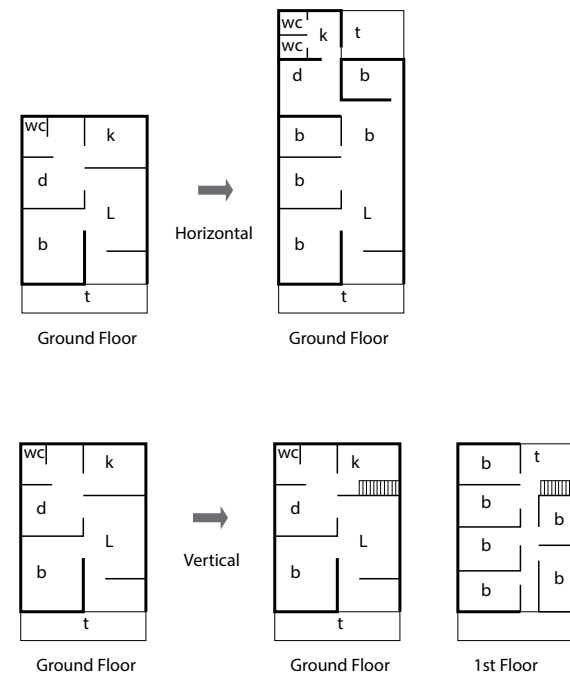


Figure 1.3 Two ways of extension of house, redrawn by the author on the basis of Funo's research (2005)



## 1.2 Affordability

In this section general affordability condition in Indonesia is first studied to provide a background for discussion. The research on proper pricing of the housing product is conducted. The research goes in two directions. One using typical calculation method to estimate the proper price according to the income level of the target group. The other uses policies and current products as reference to rethink the pricing calculated.

### 1.2.1 Housing affordability condition in Indonesia

As is mentioned before, there is a huge gap between supply and demand of affordable housing in Indonesia. However, this chapter tries to use a quantifiable approach to reflect the extent of affordability problem in the formal sector. Normally speaking, “housing affordability” means certain type of indicator, which shows the state of the market. There are different tools that can be used, including the median multiple indicator, housing expenditure to income ratio, and Housing Affordability Index (HAI). The expenditure to income ratio is used very often. Although more and more solutions are proposed as addition to this tool, it would still be a basic direct measurement.

The housing affordability in the main cities of Indonesia rates at a relatively low level among South-Eastern Asia (see Figure ). Though Bandung is the 3 largest city by population in Indonesia, it is the second worst city in terms of housing affordability in Indonesia (see appendix a.3). From housing affordability's angle,

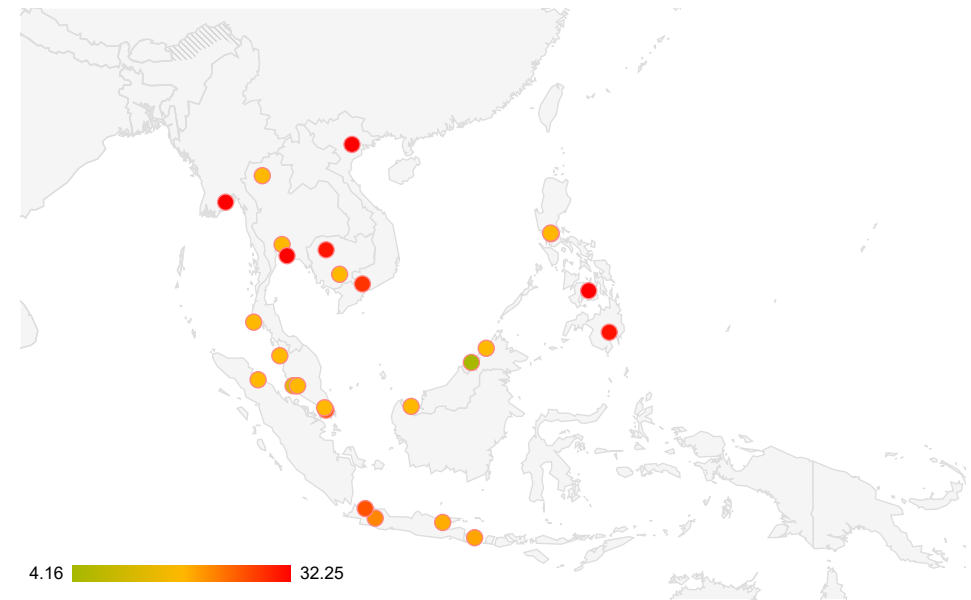


Figure 1.4 House price to income ration in south east Asia (Numbieo, 2015)

the current situation in the housing market needs to be improved.

One thing needs to be explained is that the Price to Income Ratio (PIR) might not suit every country, especially Indonesia. As is defined, PIR is the ratio of median apartment prices to median familial disposable income, expressed as years of income. Yet the price is calculated for a 90 square meter apartment. This is very different than the situation in Indonesia, where averaged household dwelling space and government recommended minimum space are far smaller than this number. This issue will be discussed later.

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### 1.2.2 Pricing of affordable housing product

The pricing of the housing product to be designed is an issue of great significance. “Affordable housing” carries the connotation of a standard (Stone, 2006), and, this standard is not absolute, it varies based on its three dimensions: affordable to whom, on what standard of affordability, and for how long (Hawtrey, 2009). However, this paper would not go into detailed discussion of this concept, but shows the results of certain chosen common definition.

The target group of the affordable housing the authors intends to design would be the households in Indonesia with relatively low or low-to-middle income. The measuring tool is price to household annual total income (before tax) ratio. A recommended ratio would be defined based on Hoek-Smit's report (2002). The financial scenario is simply set to be house purchasing, and renting is not considered. Other issues such as mortgage and financial support are neglected.

Among the data in appendix a.5, “Non-Agricultural Low Income Level Urban Household” is selected as the target group income. However, as we can see, the household income are in fact growing quickly. Since there is no data yet for more recent years, the author assumes that there is a linear relationship between GNI (gross national income) per capita and household income. According to the World Bank's data, the GNI per capita in Indonesia is \$1940 in 2008 and \$3630 (see appendix a.6). Therefore the average of per capita total income of the low income urban household group is estimated to be  $18,768,900 \times 3630 / 1940 = 35,119,000$  (IDR). For a household, the income

can be estimated using averaged personal income multiplied by 1.5 (Numbeo, 2015), which then would be  $35,119,000 \times 1.5 = 52,678,500$  (IDR).

The proper price to income ratio needs to be determine. There have been many different forms of standards in different countries and times. As is mentioned, “income” could vary from median to averaged, from disposable to total. The numerator, however, could also have many options, for example, total expenditure, total sales price, monthly rent, or monthly mortgage and so on. The author does not wish to complicate this process, and simply use product sales price to averaged annual total household income. According to Hoek-Smit (2002), for low to moderate income households in Indonesia, the acceptable house price could vary from 2 to 4 times the annual income of household, which are similar numbers to the affordable (under 3) to moderate (3.1 to 4.0) of the Median Multiple indicator (Angel, 2015).

The maximum price of the housing product (for now not considering its size) would be annual total household income x maximum price to income ratio, that is  $52\text{MRp.} \times 4 = 208\text{MRp.}$  However, according to usual definition, this number is for a house that is 90 square meters, while the standard for an acceptable house in Indonesia by policy is 36 square meters, and a large part of the current low-end housing units are 21 square meters. Since the unit-price is  $208 / 90 = 2.31\text{MRp.}$ , for each size, the maximum total price would be  $48.51\text{MRp.}$  and  $83.16\text{MRp.}$

### 1.2.3 Housing cost reference

According to the housing regulation no.1/2011 on Housing and Settlement, the Indonesian government is to provide a subsidy for 36-square-meter-house units that are priced less than IDR 70,000,000. However, this a house of this size would often cost much more in reality (Tunas & Darmoyono, 2014). As years have passed, the number has increased, but still, a number not too much more than 70M is a goal worth achieving.

There are some companies and organizations in Indonesia focusing on provision of affordable housing. Holcim provides products that price at about  $\$120 / \text{m}^2$ , which is  $1.66\text{MRp.}$ , a quite competitive number. The Habitat for Humanity organization provides basic housing units of  $25\text{MRp}$  but the size is not clear. PERUMNAS in Bandung sells houses from  $34\text{m}^2$  to  $90\text{m}^2$  with the range of price from  $87\text{MRp.}$  to  $478\text{MRp.}$  More information about affordable housing is included in appendix b.

### 1.3 Considering a specific scenario

In manufacturing, reverse engineering is a tool to develop design on the basis of given conceptual end product with certain objectives. Similarly, in this project, although the primary goal does not focus on a very specific context (since it emphasize more on a system that can generate various product), a specific scenario is selected.

This scenario is a village built for workers in the nearby factory in the Cigondewah Kaler. The aggregation of textile industries in this area has an impact on concentration of population as well. The self-built housing in the kampung provide a solution for the increasing dwellers, however, as is mentioned, this is not a plausible way for long term development. A village invested and operated by the factory or a 3rd party company with well organization and management is the way the author proposes.

It begins with the conceptual house construction company that provides adaptable, extendable, demountable and low-cost modular houses for the buyer (the factory or real estate company). When the investor have the products with different compositions, it can then rent or sell these homes to the variety of workers or immigrants. After years, as the income grows these houses can be extended to more stories. Or if these houses should be demolished due to certain changes, the components can be recycled and used in other projects.

The conceptual village should take the form of a series of linear cluster housing. The initial height of the houses should be about 2 stories, but should

be able to extend in the future. The location and context of the conceptual project is shown in figure 1.6. The information of indexes is shown in table 1.1. Figure 1.5 shows the street view near the location (Google, 2015). As the infrastructure construction in Indonesia has not come to a high level, low accessibility of construction site should be considered. This leads to restrictions on transportation and site planning.



Figure 1.5 Street view near the chosen location (Google, 2015).



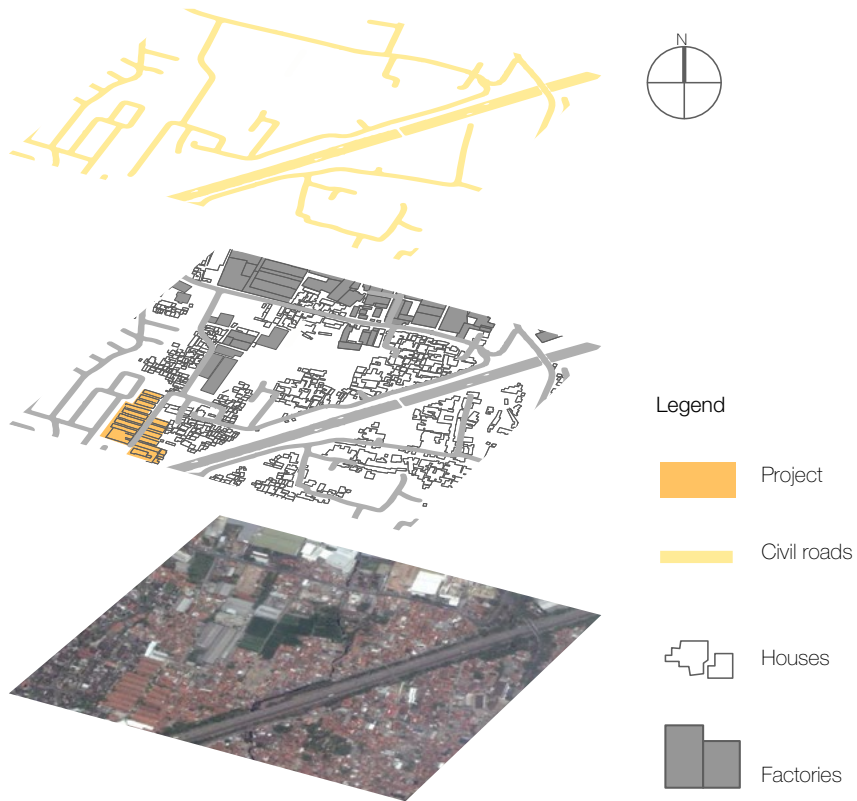


Figure 1.6 Location of the project in Cigondewah  
Kaler, own drawing

Index	value
Site Area	12128 m <sup>2</sup>
Building footprint	8000 m <sup>2</sup>
Floors	2 to 3
Total Floor Area	16000 to 24000 m <sup>2</sup>
Floor Area Ratio	1.32 to 1.98
Capacity	280 to 340 households

Table 1.1 Indexes of the project

## Part 2: Automation/robotics technology

### 2.1 Introduction

Although automation/robotics technology has been widely implemented in the manufacturing industries since the 1970s, it did not receive enough attention in the field of architecture and construction, except in very few areas (Japan is almost the only country that has used automation/robotics in construction practice in a relatively wider range). So far, aircraft, shipbuilding, automobile and many product manufacturing industries have already transformed to or been in transition to automation, yet building construction industry can hardly even be considered reached the level of mechanization-adequate machine technology, especially in the main phase of construction process, on site construction (Bock & Linner, 2015).

Traditional construction focuses mainly on labor-intensive on-site construction. Although many components nowadays are being prefabricated under the BCM (building component manufacturing) strategy, the final construction (assembly) of building (product) still rely highly on human labor. Human labor is not only incalculable, restricted to environmental condition, but also prone to danger. As is mentioned previously, increasing the productivity and efficiency would eventually ask for a scenario that robot replaces human as the main working force on construction site. However, automation does not only require utilization of robotics, but also redesign of the whole product and production line. During the design phase, consideration for future manufacturing and assembly task carried out by robots in off-site factory and on-site construction is vital for the whole cycle of automation.

According to the articles and books the author has read (Balaguer & Abderrahim, Robotics and Automaton in Construction, 2008; Bock & Linner, Robot-Oriented Design, 2015; Leyh, 1995; Howe, 2000; Balaguer C. , et al., 2002; Nof, 1999), the author summarizes 3 important aspects that designing for automation would need, for each of these books and articles would intentionally mention 3 or at least 2 of these aspects, which are: 1, robotics, concerning the knowledge of robotics or robotized machine; 2, modularity, concerning the composition of product modules, interfaces and robotic modules; 3, design principles that are needed for building product manufacturing and assembly. In the following chapters, knowledge and information about these 3 aspects are summarized and discussed.

## 2.2 Robotics

To begin with, the relationship between “automation” and “robotics” has to be clarified. Automation in manufacturing industry usually refers to the use of automatic control system to operate a lot of objects including but not exclusive to robots, process, machinery, networks etc. Robotics is an important tool in achieving automation. For building construction, although BCM (building component manufacturing) can be achieved through automated machinery, automation for onsite construction, which is a similar process to product assembly in manufacturing, would rely highly on the use of robotics. This paper pays most of its attention on onsite automation, thus robotics will be of main concern.

This chapter introduces basic knowledge about robotics, mainly solving the questions of what kinds of robots are there and what they can do. It mainly summarizes information in the works of Bock & Linner (2015), Shoham (1984), Vepa (2009), and other authors, that are essential for understanding robotics and preparing for future design. However, at some point relevance with the current site will be discussed.

### 2.2.1 Basic concepts

The definition of “Robot” and “Robotics” is not always precise enough, and vary from dictionary to dictionary. In Merrian-Webster dictionary, “Robotics” is defined as “Technology dealing with the design, construction, and operation of robots in automation”. And “Robot” is

- 1a : a machine that looks like a human being and performs various complex acts (as walking or talking) of a human being; also : a similar but fictional machine whose lack of capacity for human emotions is often emphasized
- 1b: an efficient insensitive person who functions automatically
- 2: a device that automatically performs complicated often repetitive tasks
- 3: a mechanism guided by automatic controls

In this paper, the term “Robot” is clearly closer to the 2nd and the 3rd definition. Robot does not have to be delicate robots that resembles human, but can be machinery certain characteristics. In wider sense, there are usually several common aspects of robot, throughout the literatures the author has found:

1. A mechanical structure that performs specific operation
2. An actuating system that moves the structure
3. A sensory system that gather information in the environment (optional)
4. A Power source that powers 2 and 3
5. A computer program that process input information and controls 3 and 4

To better understand, in narrow sense, the term “robot” can be defined as “a mechanical arm, a manipulator designed to perform many different tasks and capable of repeated, variable programming” (Shoham, 1984), with emphasis on: 1, the mechanical arm; 2, flexibility. Flexibility is of great importance, since it is basically what distinguishes “flexible automation” between “hard automation”.

In a hard automation, any changes to the assembly process would require great effort in rearranging the machine array. The characteristics of fast re-configurability and re-programmability of robot are essential factors that enable higher efficiency in the production process.

A manipulator is often the simplest form of robot. However, a robot can be a system that is developed on the basis of extension of the manipulator. There are many types of robots according to their levels of extension (see figure 2.1). Yet the author does not go into discussion with complex system for now, but only discuss basic concepts.

A manipulator can usually consists of a several parts (Figure 2.2). First is the controller that receives instruction from human/program, and interpret it into machine-readable codes which defines the motion of the mechanical arm. Then there is the base, with which the mechanical arm is fixed to wall, ground or ceiling, or attached to rail/mobile vehicle to make it a movable robot. Then comes the mechanical arm, which will be discussed further later. To move the mechanical arm, drive/actuator will be needed. A mechanical arm usually solve the main positioning activity, but handling the workpiece would require certain types of end effectors, for instance, a gripper. In some cases a sensor would be used to receive environmental information or workpiece status, which would then be fed back to the controller to calibrate or perform higher precision operation. All these parts forms a basic manipulator unit, which can be further

extended or integrated to become larger and more complex robotic systems.

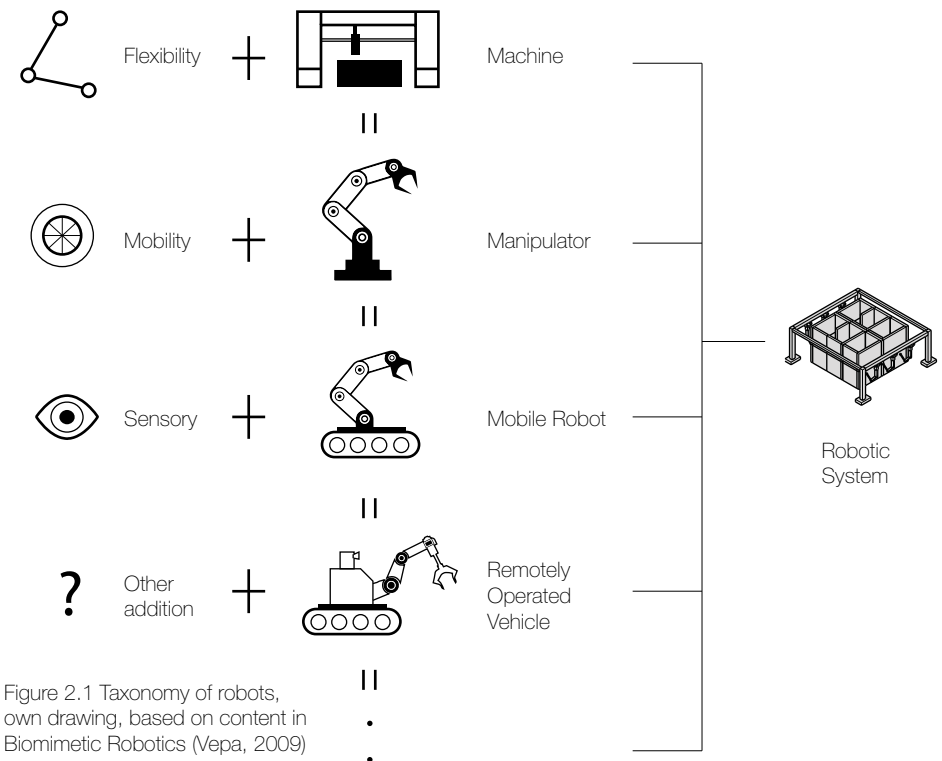


Figure 2.1 Taxonomy of robots, own drawing, based on content in Biomimetic Robotics (Vepa, 2009)

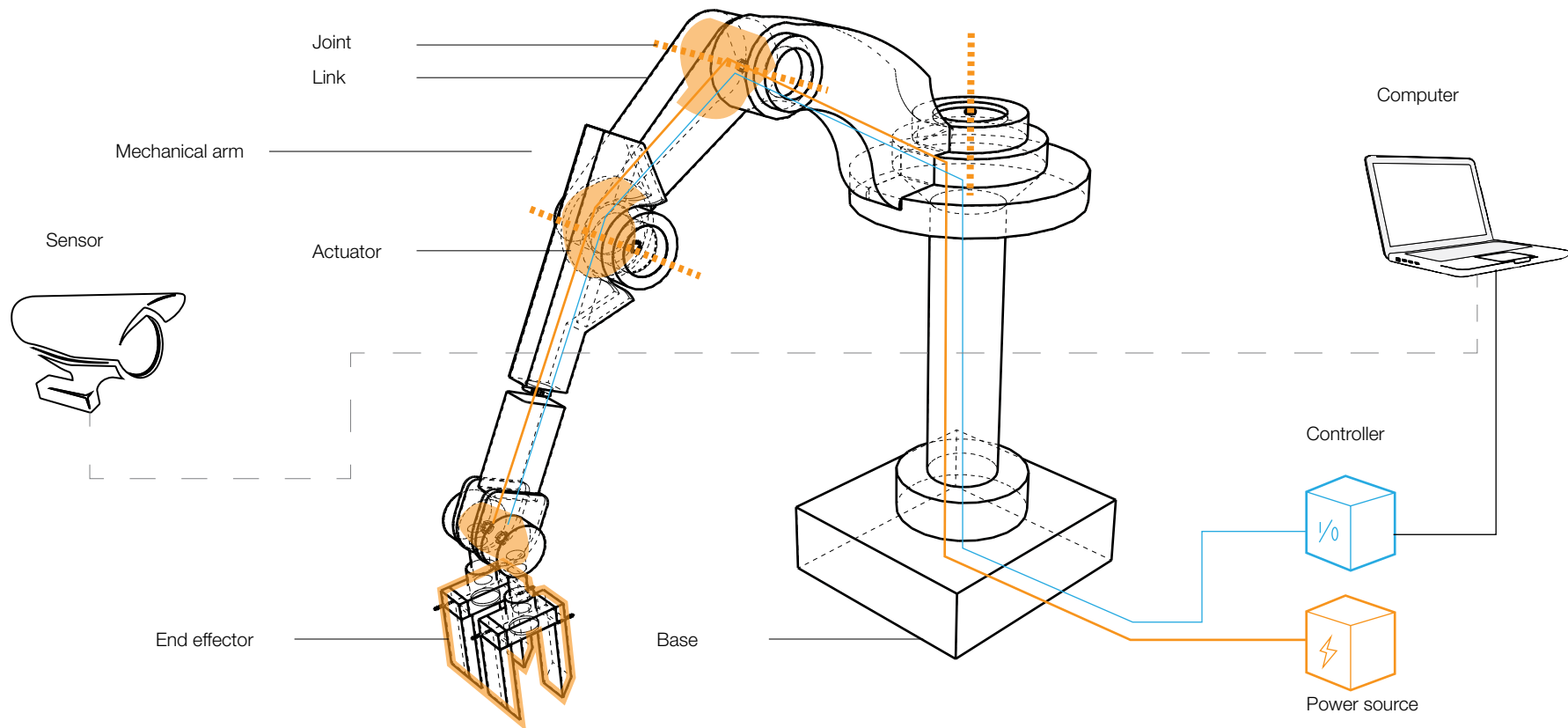


Figure 2.2 A common robotic manipulator and its composition, own drawing



## 2.2.2 Kinematics

The mechanical arm is the main body of a manipulator, and it defines the kinematic characteristics. It can be composed of variety of kinematic components, of which rigid kinematic links are often most essential. The interconnection between these links are kinematic joints. Links and joints are basic entities in a robot. There are mainly three type of joints: prismatic, revolute, and spherical (Figure 2.3). The number of joints is often referred to as “degree of freedom (DOF)”, each provides one freedom in x, y, z direction or a, b, c orientation. However, a spherical joint is special, it provides 3 DOF in orientation. More DOF means more flexibility, however, the complexity of design, control and maintenance, and cost also increase. To achieve high efficiency, the number of DOF needs to be carefully considered and usually designed to be the minimum that is applicable.

According to the different combinations of joints and links, various types of geometrically definable working envelope are generated. Also, normally, different types of robots can be defined according to the three joints closest to the base, for these joints basically defines the main positioning activity of the mechanical arm. These types are usually named according to their working envelope defined by the first three joints, or the order of these joints.

The combination of joints not only defines working envelope, but also determines the mechanical rigidity and the extent of ease of control (Shoham, 1984). There are several common types of manipulator and each has different characteristics (Table 2.1).

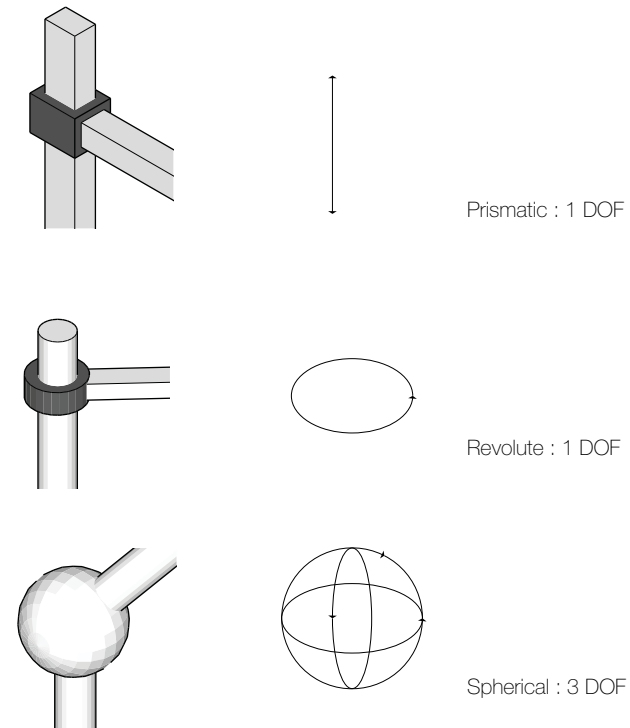


Figure 2.3 Common joint types, own drawing

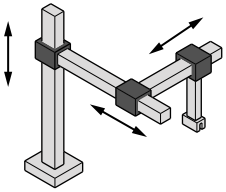
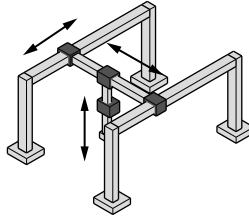
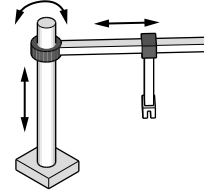
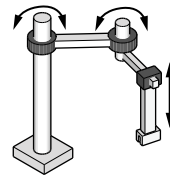
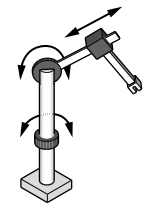
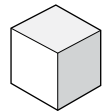
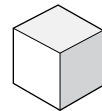
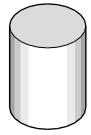
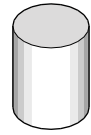
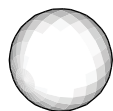
Example					
Work Envelope	 $L1 \times L2 \times L3$	 $L1 \times L2 \times L3$	 $\pi \times r^2 \times L$	 $\pi \times r^2 \times L$	 $4 / 3 \pi \times r^3$
Name	Cartesian	Gantry - Cartesian	Cylindrical	SCARA - Cylindrical	Spherical
Order of joints	P - P - P	P - P - P	P - R - P	R - R - P	R - R - P
Description	Suitable for linear motion, medium rigidity, balancing strategy required for asymmetric form	Suitable for linear motion, very high rigidity, less required balancing, but takes much space	Common model for tower cranes, balancing required, medium rigidity, suitable for handling in vertical direction	Selective Compliance Articulated Robot Arm (SCARA), very high flexibility in x-y direction but rigid in z direction, high rigidity, common for assembly of smaller elements	High flexibility in 3D, but with low rigidity, suitable for jobs that need sophisticated positioning and relatively light

Table 2.1 Common robot types, own drawing

### 2.2.3 Actuator

While the mechanical arm defines the kinematic characteristics, like the skeleton of human body, the actuator provides the power to move the arm, like the muscles. The actuator can also be classified into many types. There are mainly 3 ways to classify actuators: 1, by geometrical characteristics; 2, by power source; 3, by allocation of the actuator. The actuators in a robot are often multiple, for there are a number of joints and also the end effector would need to be driven by actuators.

As is mentioned, there are prismatic and revolute types of joints, and so is the actuator. A revolute actuator is the basic form, and it is usually a motor powered by either electricity, liquid or gas pressure. When the motor spins, the load attached to its axis is moved by rotation. A prismatic actuator would be a hydraulic or pneumatic cylinder. Linear motion may result from rotary motion which is transferred through leadscrews, rods or other conveyor that convert rotary motion into linear motion.

However, the most common way to classify actuators is by power source. There are mainly 3 types: 1, electric actuator; 2, hydraulic actuator; 3, pneumatic actuator. The electric motor is powered by electric current, and provides rotary motion. A hydraulic actuator usually uses pump to compress oil to create difference in oil pressure in a cylinder, which then creates pressure to move the part in the cylinder, such as pistons. A pneumatic actuator is similar to hydraulic ones, but uses air instead of oil.

The allocation of the actuator is another important aspect. According to the position of the actuator, they can be classified as direct actuator or indirect actuator. If the actuator is located at the joint that it moves, then it is a direct actuator. If the actuator is far from the joint, and the motion is transferred through conveyors, e.g. rods, chains, leadscrews, and gears, then it is an indirect actuator. Since the actuator would often have considerable weight, the different allocation strategy would have their own advantages and disadvantages as well. A summary of pros and cons of these actuators is shown (table 2.2).

## 2.2.4 End effector

The end effector is the tool that the mechanical arm use to get contact with the workpiece. For each tool, usually a tool center point (TCP) is defined, which is concept used to describe the position and orientation of the tool. Through the advancement of industries that deals with physical product, there are many types of end effectors that are designed for various steps in manufacturing. Nowadays end effector is often a modular part separated from the robotic arm, which means that a robot can change the end effector to deal with different jobs. There are a number of types common end effectors (see appendix d.3), which can be suitable for various construction tasks. While there are many shop products for selection, it is also common to develop specialized tool for specific tasks.

	Electric	Hydraulic	Pneumatic	Direct	Indirect
Pro	most common used	high and constant moment at various speeds	high and constant moment at various speeds	high precision of joint operation	lighter mechanical arm
	very high precision	high carrying ability	very high velocity	high power through direct transmission	changeable revolute velocity
	simplicity of control	high precision	ease of maintenance		
	ease of maintenance	can work long at high moment without damage	can work long at high moment without damage		
	relatively low cost		low cost		
Con	the moment changes as speed varies	expensive energy source	low precision	heavy weight of the mechanical arm	less precision
	heavy load would damage the motor	extensive and expensive maintenance	vibration when it stops	constant revolute velocity	less power
	low output to weight ratio	risk of oil leaks			

Table 2.2 Pros and cons of different types of actuators

### 2.2.5 Robotic system

Construction automation would need multiple types of robots. Some current robot products and automatic cranes with their specifications are listed in appendix e. However, it is obvious that simply using manipulators is far not enough to accomplish construction automation. Although manipulators with simple conveyor and feeder are capable of building component manufacturing (BCM), it is very limited in work load, work space, and process methods, and thus almost impossible to finish a complex building project. In reality, it is quite usual to use a complex robotic system. Small manipulators can be mounted on larger robotic structures to become able to reach local tasks in a relatively larger construction site, or be mounted on autonomously guided vehicle (AGV) or rails to become a movable robot that moves within the construction site. Another approach is to robotize conventional construction machinery by adding computer numeric control features, which is often an easier way (Balaguer C. , et al., 2002).

According to Howe (2000), there are three types of robotic systems. Their definition and examples are summarized as follows (also see Figure 2.2).

1. A collection of independent robots with specific function and are not arranged in a systematic way. This type is not a typical “system” since each robot deal with their own local task and do not form an integral. Examples include task-specific robot for cladding, painting and maintenance of exterior walls, and robot for element handling task.

2. A collection of robotics that forms a systematic factory like stationary construction system. One example is the AMURAD (Automatic Up-Rising Construction by Advanced Technique) developed by Kajima Corporation in Japan (Bock, 2013). The system in a complex onsite factory that pushes up each floor after it is constructed. In practice high-rises up to 9 floors can be built with this system.

3. A collection of robotics that forms a systematic movable factory that moves itself while constructing each part of the building. Examples are ABCS (Automated Building Construction System) (Shikawa, Ohkawa, & Mori, 1994) and the Big Canopy (Wakisaka, Furuya, Inoue, & Shiokawa, 2000) by Obayashi Corporation, and SMART (Shimizu Manufacturing system by Advanced Robotics Technology) by Shimizu Corporation etc. Although being developed for different types of building (precast concrete/steel) and by different corporation, they share many characteristics. Each uses a climbing platform to construct the levels of building and moves itself up after one floor is finished. Khoshnevis (2004) demonstrated several robotic systems for contour crafting. There is one climbing the building as it builds, and another moves horizontally. As for AGV mobile robot, the situation can be very complicated, since it needs to position itself without predetermined work path and deal with relatively less stable working base, and it is seldom seen in precedent projects, unless only for simple material or standardized block handling.



## Conclusion

Considering the object of design in the specific context - a multi-story housing cluster for workers of the factory in kampung area – and the goal to use higher degree of automation on construction site, the third type is likely to be used. The first type does not strictly forms a robotic system, and is more suitable to aid in conventional construction to replace in heavy, repetitive and dangerous tasks. The second requires a sophisticated stationary system as it not only builds but also pushes the total weight of the building. It can be suitable in high-rise construction that has relatively small footage. The third type can be built into a lighter form. It does not need the full space of the building footprint, and only need to move itself as it build – which is also a restricting condition that require lighter structure. Since the stories of the intended building is not high and is more linear horizontally, a movable robotic system in horizontal direction is a preferred option.

However, even though choice of type of robotic system is made, suitable detailed design of the robotic system for the project cannot be simply judged. It requires careful consideration together with modularity of the project, including the modular system and interfaces, which will be discussed in the next chapter.

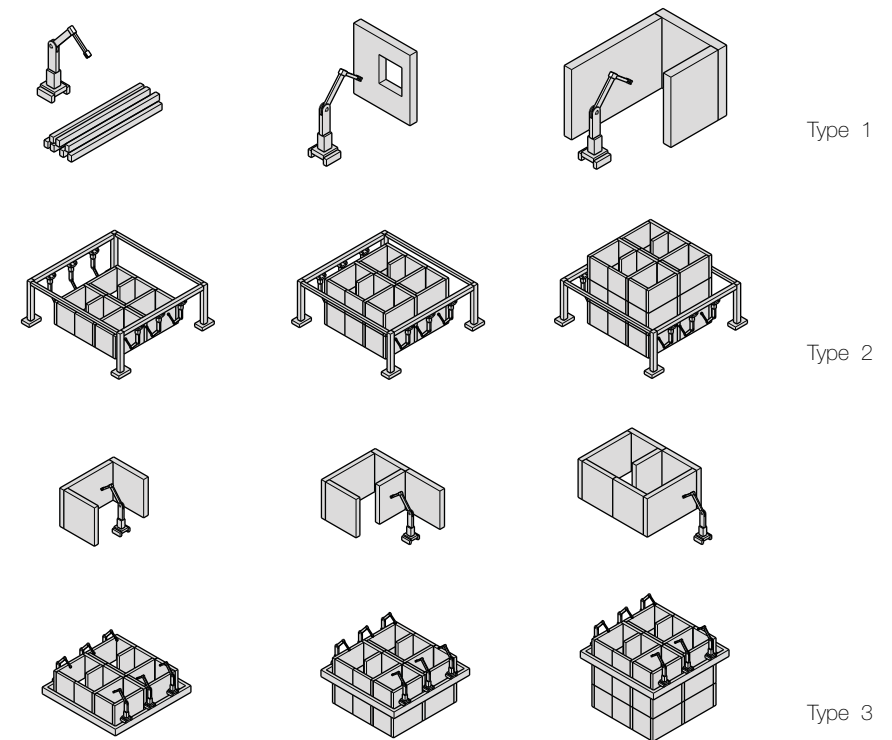


Figure 2.2 Different strategies for robotic system, own drawing

## 2.3 Modularity

Modularity is an important term not only in construction, but also in design and the production facility itself. It is the key to provide customizable products while minimizing the time and resources consumed in design and production process. There are many aspects of modularity. Bock (2014) suggested that modularity should be distinguished between one that serves the manufacturer and the other that serves the user. Thus the following types can be defined.

For manufacturer related aspect, there are modularity in: 1, product development; 2, production of product; 3, logistics/sourcing. For user related aspect, there are modularity in: 1, sales; 2, use of product; 3, end-of-life. These categories can either be identical, linked or even different. However, normally it is more practical that the modular structure is aligned in as many aspects as possible, for it lowers complexity and improves efficiency.

The author does not go into discussion about modularity other than development and production, and, for further simplification, mainly regard them as a whole. To realize this modular system, not only modularity in the product structure, but also in the interfaces and production tools are needed. They work as subsidiary aspects of the modular system. In the next paragraphs, general concepts about product modular strategies and interfaces are discussed. However, since modularity in the production tool, for instance, changeable end effector, extendable robotic units, is mentioned previously, they will not be covered in later text.

### 2.3.1 Modular strategies

The modular systems in manufacturing industries are often based on two types of strategies: 1, platform strategies; 2, Frame & Infill (F&I) strategies. In construction, there is also the block strategy. The platform strategy is basically developed in automobile industry. It is a product development method where a series of products share certain same components (Olson, 2008). By sharing components the cost is greatly reduced and new models can be developed more quickly and with more convenience. Many precedents projects in construction, according to Bock (2014), many can be categorized into the F&I strategy. In F&I strategy, first there is the bearing frame structure that serves as a base, then the infills, such as modules, components, parts can be subsequently mounted to it. To a certain extent, the frame can also be understood as a “platform”. The block strategy features mainly 2D or 3D standardized blocks which compose the structural wall or large building module of a building. Below introduces some modular system that exist theoretically or in reality. More detail of these projects is in appendix c and e.

#### Open Building approach

The open building approach researched by Habraken (1978) is a kind of F&I strategy. The idea is that buildings can be more open and change according to user needs. Habraken introduces the term of levels, on each level the elements are managed by different people. The levels do not only exist in a single building, but it can also be extended to the urban scale. In a building There are levels of: 1, furniture, managed by user of the room and can be

changed within few years; 2, interior finishing, controlled by the owner of the building, can be changed at about once a decade's rate; 3, building itself, which refers to structural elements and enclosure that is difficult to change, is also controlled by the owner and can be changed after decades' time. The open building mainly focus the open end use of design and use. In fact, the open end use has already become a common sense in many cases. Not only can the finishing, interior segments be rearranged in residential buildings, but it has been a normal phenomenon in offices and commercial buildings, where the spaces are often undefined for the company or shop to customize.

Futurehome: 3D + 2D

The EU Futurehome (Balaguer, 2003) is a project that aims to develop new a modular building system with integration of construction automation. The project has two types of modules: 1, 3D modules, composed of beams, panels, installations and accessories etc.; 2, 2D modules, composed of wall frames, panels, windows and doors etc. In fact it is partly an F&I strategy, since the beams in the 3D modules form the main frame, and the 2D modules are installed on 3D modules before on site assembly. It can also be regarded as a block strategy on the larger scale, since 3D modules are eventually assembled on site. The design method of the project is based naturally on the modular system. Although there are two ways of design, using a module catalog to compose design is evidently more suitable than designing traditionally in the beginning and translating it into modules in later stage. The customer can

decide together with the architect the layout of 3D modules and selection of 2D modules. The design is then generated through these selections and translated into production files.

SMAS (Solid Material Assembly System): standardized wall component  
This system is developed by researchers in Japan (Kodama, Yamazaki, Kato, Iguchi, & Naoi, 1988), using a 6 DOF robotic arm to stack building blocks to construct bearing walls. In real construction, the robot can be mounted to a properly designed rail, and moves while constructing different parts of the building. This system is totally a block systems, and it does not use any structural frame. Whether it can be built into higher stories is unclear.

Modular house products

In the current housing market, modular prefabricated house has been gaining more and more share, especially in the US and Japan. There are many companies that produce such product. There are famous ones such as Sekisui Heim, Toyota Home in Japan, and Livinghomes, Connect-homes, Champion homes, etc. in the US. Similarly, many of these products are created with the F&I strategy within each building unit, and block strategy on building complex scale, and use similar logic in design and management as well. A house can be composed of several modules, each prefabricated in factory with either high or low degree of automation based on their industrialization level. Each module has a structural frame, mostly steel frame, and customizable infills,

including interior and exterior finishing, interior separation, doors, windows etc. When a customer select the floor plan and finishing option from the company's database and make the order, the customized modules will be prefabricated in the factory. After prefabrication, the modules will be mounted to trucks and transported to the construction site, where they will be assemble one by one with a crane. By this process, a home is constructed in a very efficient way. During prefabrication, unpredictable environmental change is avoid in the factory, and the process is safer and faster with implementation of automation technologies. The on-site assembly process of one house may even take less than one day (TOYOTAHOME channel , 2013).

## Conclusion

The F&I strategy seems to be an ideal option. Because of the structural nature of building, it is often better to have stiff structural frame when it needs to be built into multi-storeys, otherwise heavy wall elements should be use, which is not efficient. On top of the structural frame, enclosure and installations are needed to make it functional. Thus the F&I strategy in manufacturing fits the building that needs structural frame and enclosing, functional elements intrinsically. There do exist robotic construction experiments or products that are based on stereotomic design, such as on site robotic construction researches done by ETH's fab lab (Helm, 2014), and those done by Hyperbody in TUD (Feringa, 2014), but they mostly deal with conceptual/futuristic walls/arches and do not view from the angle of entire modern building. There is also construction automation based

on concrete contour crafting, but since concrete construction is considered permanent and difficult to be recycled, contour crafting might not be a good solution in Indonesia, as the development is fast and changes to society and families can be swift. Based on the experience of the author, in developing country a building might be demolished or need to be upgraded after decades if it is not the type that is designed and constructed for permanent use. Thus the use of concrete for not fully certain building is not recommended. These are one hand, and, on the other, F&I strategy is applied in many existing products, and some are partly integrated with automation technology. As for the project, F&I strategy have the capacity to meet various need of the customer, and can theoretically be relatively easy to extend or be demounted. Thus the author choses F&I strategy as the current direction.

While being flexible to design and manufacture, there are also drawbacks shown in the existing products of this strategy. Since modular building blocks are prefabricated as a whole with either modular or non-modular infills, their weight tend to be considerably heavy, which creates great challenge for onsite automation. Not only for most modular housing products in the US, but also those in Japan, where relatively advanced construction automation technology is often applied, although automation is used in prefabrication process, on site assembly is still done with traditional mobile construction cranes and human (TOYOTAHOME channel , 2013). In Futurehome project, a robotic assembly system is designed to connect the 3D modules, but this system requires even larger space than traditional ways, not to mention that this system needs to be

firstly build onsite and be demounted after construction, while a mobile crane is more flexible.

Another issue is that considering the context of project, where the accessibility of the site is not very good (only small one lane civil road of about 2.5 meters), large 3D modules seems to be impossible. Besides using smaller modules, like the size of a 20 feet container (2.44m x 6.06m x 2.59m), there exist other options, for example, raising the frame modules on the construction site with relatively simple robotics and install enclosing module after it. Or it could be that the frame is also assembled on site, using a same robotics system as the infills. Anyhow, the author does not draw conclusion here, and would leave it for later research and design.

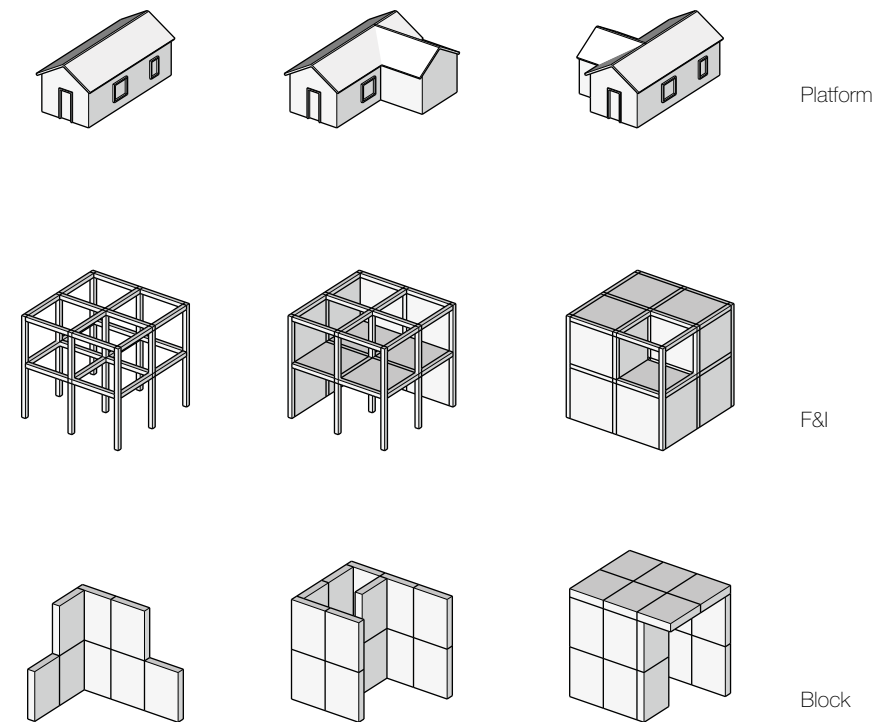


Figure 2.3 Different strategies for modularity, own drawing



### 2.3.2 Connection Interfaces

The connection between parts is an eternal topic in all architecture. It is essential to develop proper connection between building elements, especially for modular components and automated operation. The modularization of building products together with development of standardized interfaces and connectors are important topics in many construction automation researches (Bock & Linner, 2015). For the modular aspects, standardized interface allows plug and play installation of whatever modules, which is the key to customization. To take one step further, if modular housing industry is to develop into a multi-tier manufacturing mode, modules produced by different supplier can be used seamlessly in the product, which would greatly improve overall efficiency, as did in manufacturing industries such as automobile, aerospace, and one that is more widely known, consumer electronics.

For automation, the design of interface would have another concern. Robotics has advantages such as speed, repetitiveness, etc., yet it can hardly match human in terms of intelligence and flexibility. Although sensors, artificial intelligence, multi-axis robotic arms are developed to overcome these weakness, designing suitable connection that require less robotic complexity would be a more efficient solution.

#### Categorizing interfaces

There are many types of interfaces. Bock (2014) suggests that interfaces can be categorized in 4 ways: 1, intensity, considering the surface of connection

and strength; 2, connector elements number; 3, function of connection; 4, repeatability of the connector. Because there are building elements of different function, such as structural elements, enclosing elements, and service elements, and that the end effector needs to get contact with the element, the author choses to categorize interfaces according to the type of element they connect, which are:

1. Structural – structural, connection between structural frame modules or structural elements;
2. Structural – enclosing, connection between structural elements and infill 2D elements, such as walls, roofs, and floors;
3. Enclosing – enclosing, connection between 2D elements;
4. Service – service, connection between service elements such as installation, facility and appliance, and embedded pipes and wires in 2D elements or structural elements;
5. Robot – building element, connecting parts/indicators for ease of robotic operation.

The design of interfaces should take into consideration at all time the properties, especially the modularity of the elements and operational characteristics of robotics.

## Precedents

There are some precedents of interfaces design than can be learned from:

Structural – structural: In Futurehome project (Balaguer, 2003), a universal cone shape connection between 3D modules is designed. Considering the on-site precision of robotic cranes, cone shape is considered suitable to deal with the tolerance. Similar treatment can be seen in the Big Canopy (Wakisaka, Furuya, Inoue, & Shiokawa, 2000) and ABCS (Automated Building Construction System) (Shikawa, Ohkawa, & Mori, 1994) developed by Obayashi. Although the way of construction is very much different - ABCS is built for a relatively conventional steel structure high-rise, and Big Canopy is for high-rise with precast concrete – the connection between elements are specially designed for convenience of unmanned robotic assembly and welding.

Service – service: The Futurehome project also developed a pair of connectors that is suitable for automatic connection of pipes and wires. In the research of Khoshnevis (2004), an industrial bus-bar like module for wire connection is designed.

End effector – elements: The connection can be greatly affected by the end effector chosen. Possible ways include: using proper common gripper for the element; designing additional parts in the element (Howe, 2000); designing specialized gripper (or other end effector) that work with the element/specialized

additional parts (Bock, Herbst, Balaguer, & Abderrahim, 2000). The recognition process of the elements may need another type of interface. RFID (Radio Frequency Identification), barcode, or QR (Quick Response) Code may be used for the sensor to recognize and position the element. An example is the RCACS (Robotics & Crane Based Automated Construction System) developed by Korea University (Kang, Changjoo Nam, Lee, Doh, & Park, 2011), where two QR codes are tagged on the structural elements.

## Conclusion

The interfaces mentioned above are results of consideration of modularity and automation at the same time. However, the connection for enclosing elements seems to be rarely seen. Even in Japan's modular housing industry, the assembly of these elements are still often done by human (TOYOTAHOME channel , 2013). The reason could be multiple. On the one hand, these elements can usually be quite light, in comparison with structural elements, and can even be light enough to be carried by two or one person. On the other, the installation requires relatively higher precision and intelligence, and the process is more complex. In this case, robots cannot fully use its potential in working load, and is restricted by those requirements. However, the author believes that if the elements and their connections can be redesigned accordingly, there is still possibility to use robots in this process. In the most ideal scenario, all the elements should be able to be changeable and robotic assembly available through utilization of proper interfaces.

## 2.4 Design Principles

It is evident that in construction automation, the design itself needs to be revolutionized. For the past many years, the techniques in construction has evolved to be optimized for human operation (Bridgewater, 1993). However, as is mentioned, automation tools has completely different characteristics, thus attention needs to be paid to the new tools' advantages and disadvantages. In modern manufacturing industry, the three main aspects of design, production and automation form an integrated system (Benhabib, 2003) and is considered as a whole, and so should the construction industry.

An early researcher Bridgewater (1993) suggested that there are design principles that should be applied in at least two levels: component level and machine level. The former emphasizes rethinking the way components are assembled, especially in terms of direction, and there is a principle called "strong axis assembly" where most components follows the strong axis for simplification of robotic motion. The latter focuses on the detailing the movement and jointing methods for machine, for instance, linear movements is better achieved with Cartesian robots than approximation with rotating joints, and certain guide should be applied in order to compensate the tolerance of machine. However, as Howe commented (Howe, 2000), these are not enough since they only focus on small scales and do not rethink the design from a more general level.

The book Robot Oriented Design (Bock & Linner, 2015) seems to provide better insight. It has pointed out the fact that a manufacture system is very complex and

is usually a combination of various manufacturing methods. Thus a product's design can be oriented to a variety of objectives. The book also develops the ROD (Robot Oriented Design) strategy that has a series of dimensions on the basis of the Design for X strategy in manufacturing (Benhabib, 2003), which covers a large range of design considerations, for instance product structure, robotic production, robotic assembly and disassembly etc.

However, in this paper only considerations thought to be most essential for robotic assembly would be summarized, which are: 1, geometric coordination; 2, principles for structure; 3, principles for components; 4, principles for joining. These aspects cover from the bigger scale to the smaller scale. These summaries are based on study of the works of Bock (2015), Bridgewater (1993), and Boothroyd (1992). The book written by Boothroyd is about automation assembly of product, however, many of the insights can be transmitted in building components and jointing methods.

### 2.4.1 Geometric coordination

The definition of coordination system is a prerequisite for design. In order to allocate the components in space and defining their dimensions, a grid system is needed. Bock (2015) suggested a 1D-5D coordination system for components, services, and process. In this paper, the author does not consider complex service add-ons and tries simplify the composition of components, and thus assumes that a 5D grid for the coordination system would be suitable for the project. 5D is composed by the 3 dimensions of space, 1 dimension of time, and 1 dimension of installation motion. The grid system uses band instead of simple axis, since it is easier to describe the location, dimension and also intersection of components. The grid should use limited standard dimensions. (See figure 2.4).

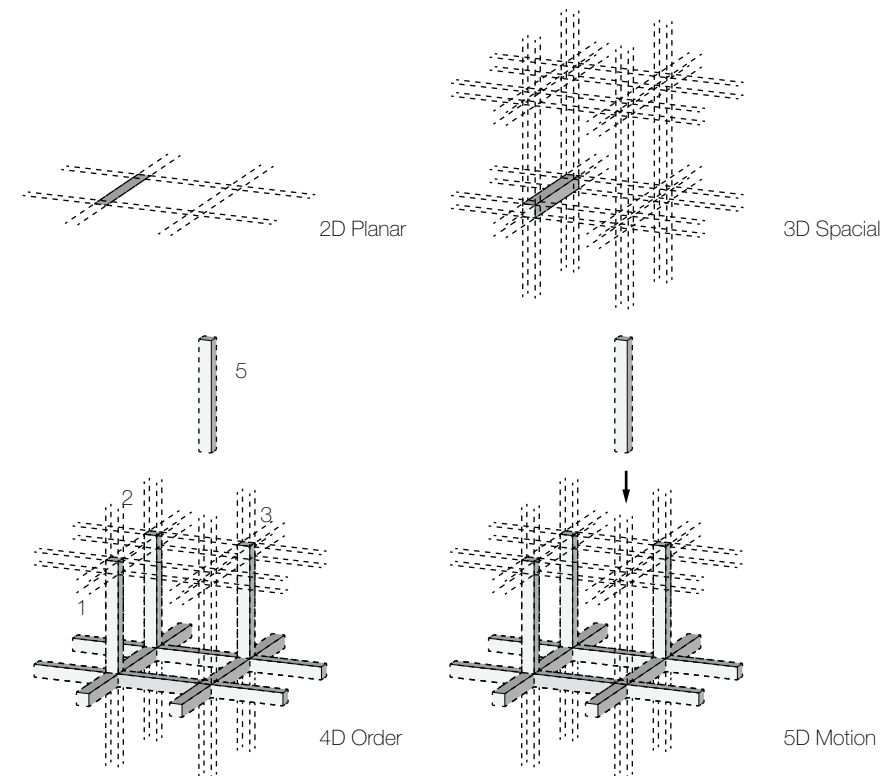


Figure 2.4 Different strategies for modularity, own drawing

## 2.4.2 Principles for structure

To clarify, “structure” here means the structure of the modular building system, not the bearing structure of a building. As is mentioned, modularity is the key to customization and efficient implementation of automation technology. In previous text, general strategies of modularity are discussed. However, having strategy that guides the direction is not enough. There should also be more detailed principles to guide the design of modularity. One aspect is the structure of the modular system. There are four main principles summarized in this aspect (also see figure 2.5):

1. Optimization of hierarchy of the modules for robotic assembly and supply. In traditional construction parts, element, and modules of different hierarchical level are processed, treated, and assembled on the construction site. For robotic construction, on site operation needs to be simplified by using limited types of modules. This would require rearranging the hierarchy of the product.
2. The number of modules and their types that need to be assembled on site have to be controlled. There are two senses in this principle. One is that in off-site factory components with high degree of integration can be produced in a stable and efficient manner. On site construction faces a lot more uncertainties, which may hinder the process. Thus the less is better. The other is that, as is mentioned, there is limitations on what robotic systems can do, thus less types of modules would be better. This can be regarded as another side of principle 1, but emphasize the number other than hierarchy.

3. Optimization of the sizes, weight and level of integration of the modules. Robotics is not only limited in manipulation and processing method, but also in motion, working space, and payload, like any other machinery in construction. Heavier and bigger components would require bigger robots, and often higher complexity and cost. This is also important for transportation. Since modules should be supplied as a whole to the robot, they need to be transport in the same manner. There is a range of different size container models, which can be used as reference (see appendix f). Same is also for on-site planning and logistics. However, as is mentioned, modules are often better to have higher integration for simplification of robotic manipulation. Thus a balance needs to be stricken between these two considerations.

4. Using integrated connector for assembly of modules. High integration level of modules means less operation and intersection on the construction site. In conventional construction, the connection between parts often takes much effort and time. In the most ideal scenario, the modules can be easily guided and connected through embedded connectors, which greatly reduces the operation needed to perform additional robotic tasks.

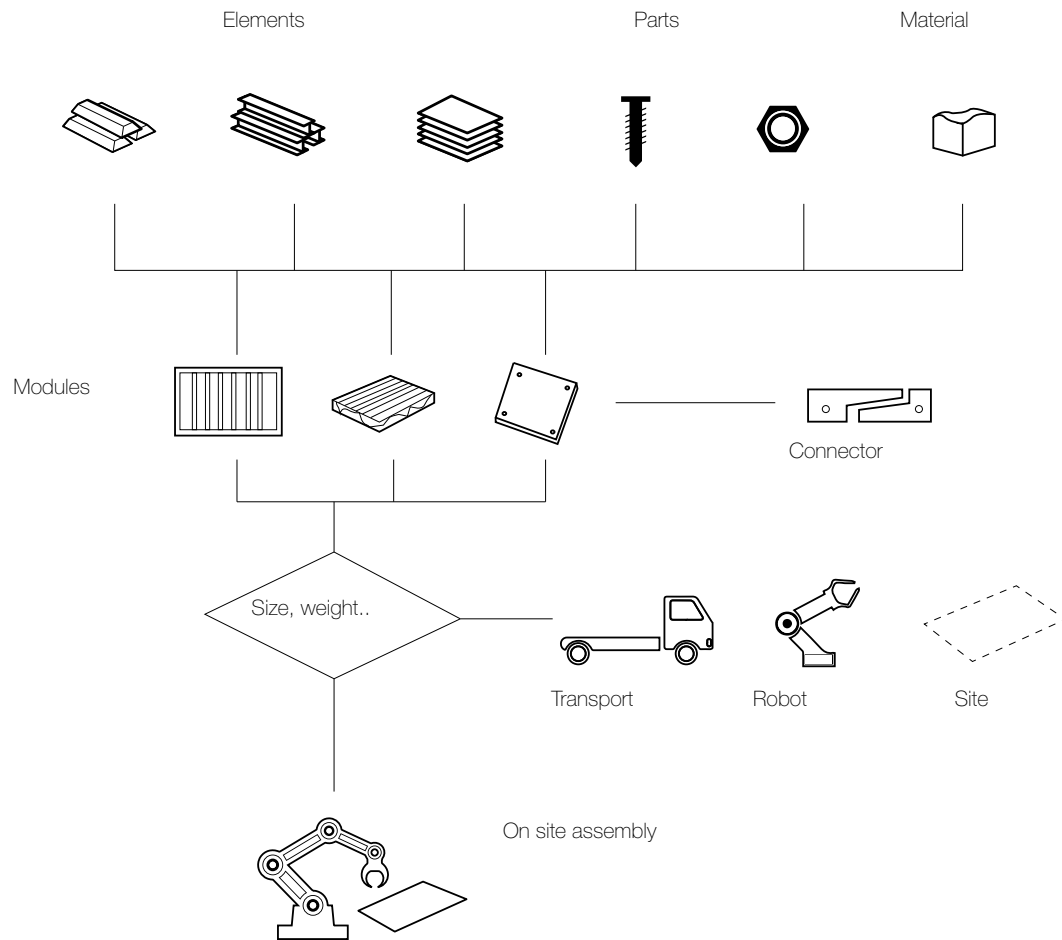


Figure 2.5 Principles for product structure, own drawing.



### 2.4.3 Principles for components

Based on the difference in each word's emphasis, in this section “component” is used rather than “module”, which pays more attention to the relationship with the larger building system. Although partially covered in previous text, the content of this section mainly views the design of components within its own level. There are principles as follows (see Figure 2.6).

1. Reduction of number of parts needed to build a component. This is a basic strategy to reduce complexity and cost. Any part that can be combined or is unnecessary should be avoided. The use of composite unit is recommended.
2. Standardization of parts, or reduction of number of type of parts. This has already been a common sense in structural design and product design, but it needs to be extended to more aspects in building component design.
3. Optimization for ease of orientation. The process of orienting a component after gripping it the feeder or before placing it in the assembly unit does not add any value but only increase complexity and cost. Two levels of consideration are needed. One is that proper orientation of supply and installation should be designed to reduce redundant operation. The other is that instead of asymmetric parts, symmetric parts should be used whenever possible, which can compensate for difficulties in certain robotic operations.
4. Assembly along Z axis. Bridgewater called it “strong axis” principle (1993). This is also a common sense in product design for automation. Because

of the gravity, assembling parts in the vertical direction has the advantages of being more stable, requiring less DOF of robot, and need not use additional support in many cases.

5. Components should be able to be handled in bulk. In the process of storage, transportation and feeding, components are often placed in a bulk manner for ease of handling. This leads to a lot of requirements for the component. For instance, rationalized shape is required to avoid tangling with each other, surface conditions need to be not adhesive, but abrasive and stand the wear of robotic handling, the stiffness and toughness need to be strong enough if the components need to stack, etc.

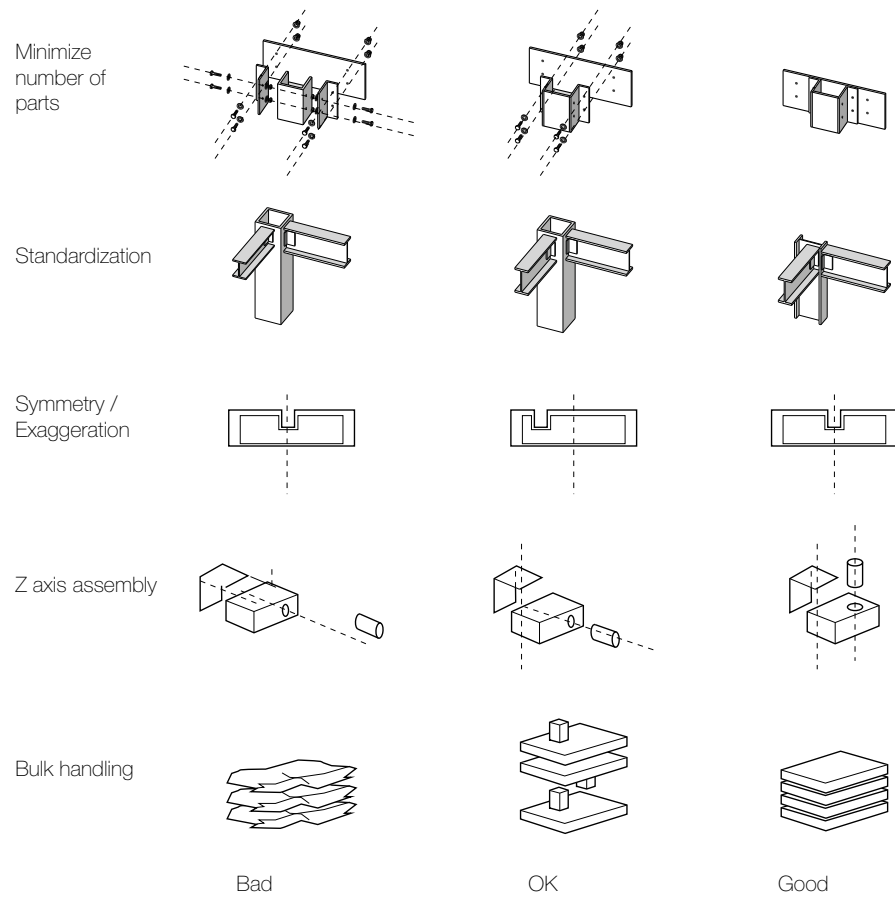


Figure 2.6 Principles for components, own drawing.

## 2.4.4 Principles for joining

In previous text interfaces of different levels were discussed. This section focuses on the design principles for their physical and logical properties. As is mentioned, it is best to have plug-and-play connectors between components. However, in reality there are still many cases that need a series of joints for the connection. Bock (2015) suggests using abstract graphical symbols to describe a joining system for ease of analysis and design. There are principles as follows.

1. Reduce the types and number of joints needed for connection between elements. Simplification is an important principle in all aspects, and of course joining cannot be an exception.
2. Use simpler joints if the elements are need not to be disassemble. Each type of joint has a number of operation needed. Usually, demountable joints would need more operation than fixed joints. For instance, a rivet joining only need placing of one element and pressing, but a bolt joining need placing of multiple elements and rotating.
3. Use self-aligning design, such as leads, lips and chamfers. Because robots, although being precise, often lack intelligence in aligning, which require sophisticated sensor and algorithm. For human, this is done naturally and easily through eyes and brane. Also, in on-site condition the precision of robots do not perform as well as in laboratory environment. Thus self-aligning design to compensate the tolerance and unintelligence of robots is essential.

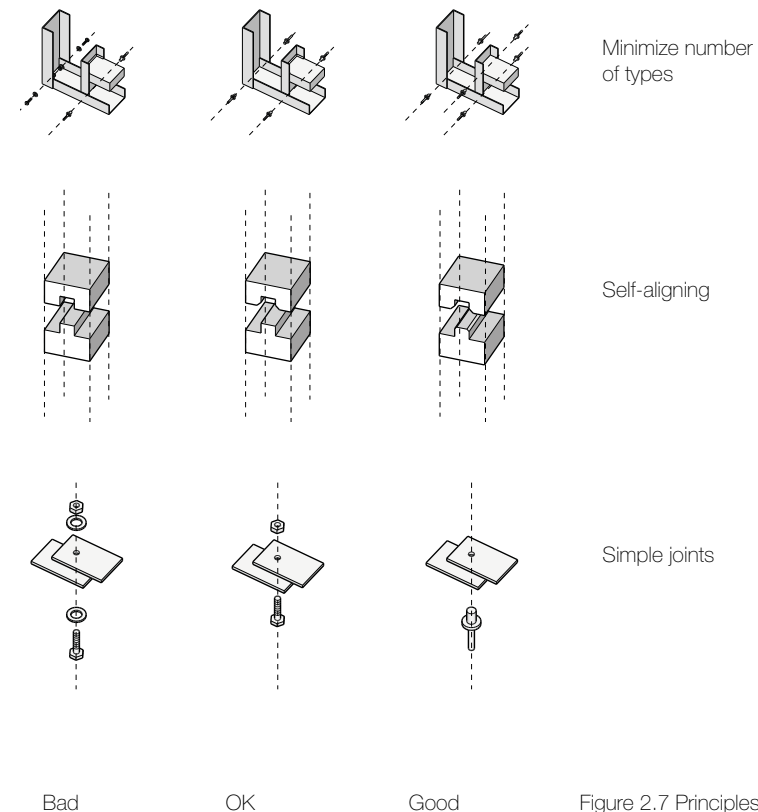


Figure 2.7 Principles for joints, own drawing.

### 2.4.5 Conclusion

The characteristics of the construction tools require changes in design from macro to micro scale. Generally, there are several ideas that runs through the scales, which are: reduce the complexity by minimizing number of parts, elements, types and operations; take into consideration the kinematics of robots; take into consideration the tolerance of robots; last but not least, consider site condition that influence on-site planning, transportation and robotic system setup. Whenever a design decision is made on each level, it should be checked using these principles.

In order to make the design easier, rather than inventing something completely new, the author choses to learn from constructions available in the current state. This process is twofold: 1, learn from precedent robotic system to pick what can be used in the chosen context; 2, learn from conventional construction methods and chose what can be relatively easier to meet the robot-oriented design principles through limited modification. A combination of the two would finally lead to a design that evolves from what is existing now.

## 2.5.1 Cost of construction system

As one of the primary goal is to provide housing that is affordable, the estimation of building cost would be an important issue. However, the factors that are influencing the total capital cost are too many (see figure 2.8) to be analyzed in this paper, the author would only focus on the capital cost of the construction system, which replaces human labor with automated mechanism.

Conventionally, the composition of construction cost is shown in Figure 2.9. What the author is trying to estimate -the cost of the construction system - is in fact "Installation" among these aspects. According to Boothroyd (Assembly Automation and Product Design, 1992), there are four aspects of estimation need to be done, which are:

1. Total cost of general-purpose equipment
2. Total cost of special-purpose equipment
3. The average assembly cycle time
4. The cost per assembly of manual labor involved

In order to perform the estimation, the possible parts of a robotic system are summarized here. In existing robotic construction systems, the general-purpose equipments may include following major parts: 1, hydraulic telescoping cylinders that climb on the columns and move the system; 2, robotized overhead crane; 3, elevator for transporting construction elements and materials. The special-purpose equipment may include the specially designed end-effectors that operate the elements and carry out specific joining process. The assembly time

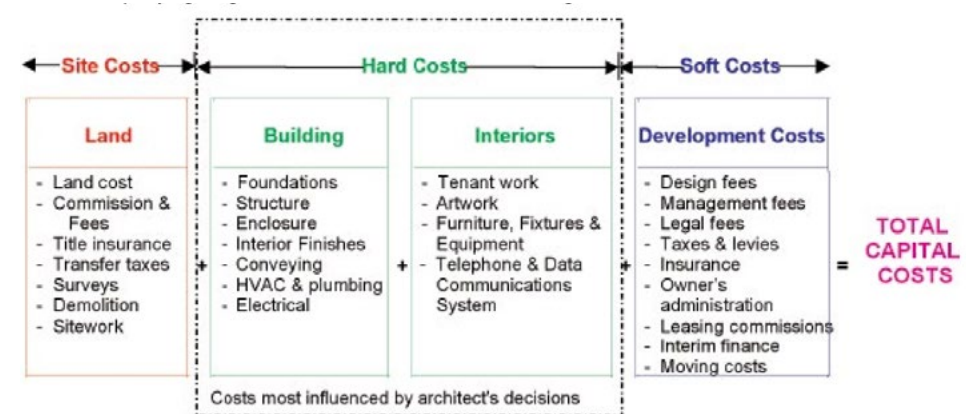


Figure 2.8 Capital Cost Components  
(Construction Cost, AIA Bank, 2013)

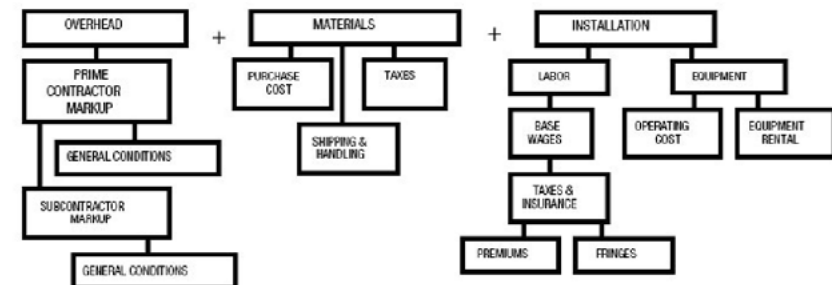


Figure 2.9 Construction Cost (Construction Cost, AIA Bank, 2013)

aspect is difficult to calculate. The author would simply use the experience from previous projects. In project ABCS, for construction of a 40 storey building, conventional construction cost 6 months, and ABCS cost only 2.5 month. Thus the time cost by a robotic system is seen as 42% of conventional system.

Although the labor used in a robotic construction system is less than in conventional ways, some workers are still needed to be on site for supervision, maintenance and possible operation that need too much dexterity and precision for the system. It can be imagined that work such as installation of finishing, fixtures, and equipments are more possible to be handled by human.

For comparison, the cost of conventional construction for a comparable project is also needed. The cost has two aspects. One is the labor, and the other is the equipment. As both labor and equipment are used in a rental way, the time consumed should also be considered. After the design of this project is done, the two costs of a comparable project with the construction time should be gathered and compared to that of robotic construction system.

## Conclusion & Discussion

### About Part 1

This part looks into the increasing housing need in Indonesia. Three aspects are studied. First, general spatial, formal and progressing aspects of existing housing typologies, to be used as reference in later design. Second, affordability issues are also studied, setting a general goal that should be achieved. Third, a specific scenario, as the site that the conceptual design is to be place on.

The housing project should be designed considering all these aspects from the context, from larger to smaller scale. The project needs to have adaptability to different combination of spatial units in a relatively compact way. The sales price should be set within an acceptable range. And it should socially and spatially fit into the specific context.

#### Limitations:

As the author has not been to the context in person, some needs that are important might have been neglected. The research of this part should be extended after field research. Especially material and ornamental aspects of local housing needs, which are less discussed in literatures, might also be of great importance. The specific scenario also needs further investigation.

### About Part 2

This part studies the general knowledge and common strategies used in design of robotic systems. There are 5 main aspects. First, basic knowledge

of composition and principles of robotics. Second, modular strategies used in robotic system. Third, design principles for product in robotic automation. Forth, method to estimate the cost of robotic automation system.

There are in fact three aspects that should be designed. The first is the robotic construction system, including its composition of structure, actuation and sensory, and the computer program that processes information and provides control. The second is the building system, which includes all the elements, components and modules that are operated by the robotic construction system. Generally, the construction and building systems should be as simple, light weight and operable as possible, and should be designed as an integral as they are closely related and influencing each other. The third is the building typology, which has limitation from the building system and is informed by the knowledge in part 1. The relationship between these 3 aspects and the research that support them is shown in Figure 3.1.

#### Limitations:

The research of robotics is very basic and thus the design of robotic construction system would not be detailed but would rather be a conceptual one with essential parameters. In fact, the design of such system in reality should deal with a lot of engineering issues and require calculations and experiment, which is beyond the author's capability.

The design of building system would also need knowledge of existing building

products, since it is too difficult to invent something completely new and the better way is to try improving existing products for robotic automation. The amount of types of existing products is very huge, and is difficult to discuss in detail. However, the author should continue to research by designing with certain chosen products.

The estimation of cost is another tough issue. As is mentioned, there are too many factors that influence the total cost. The cost of the construction system is just one part of construction cost, and construction cost is merely one small part of total cost of the building. In this project, the author is only trying to give preliminary estimation of the construction system itself, the others are neglected for now.



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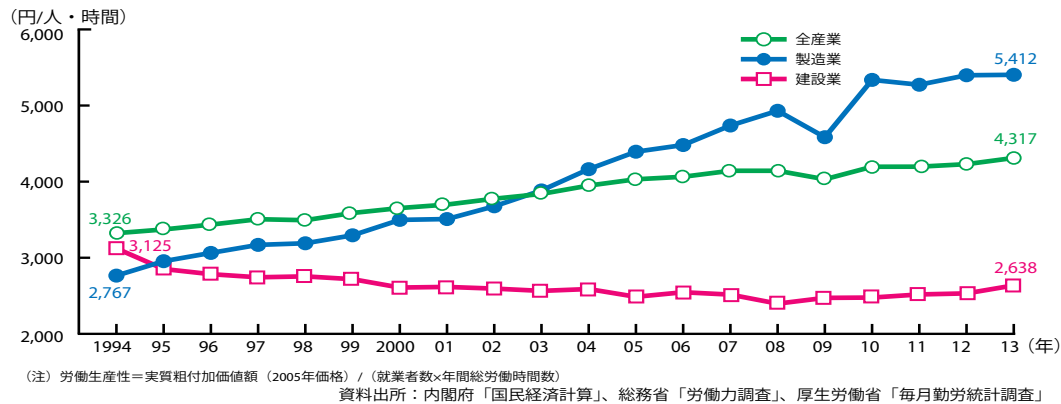
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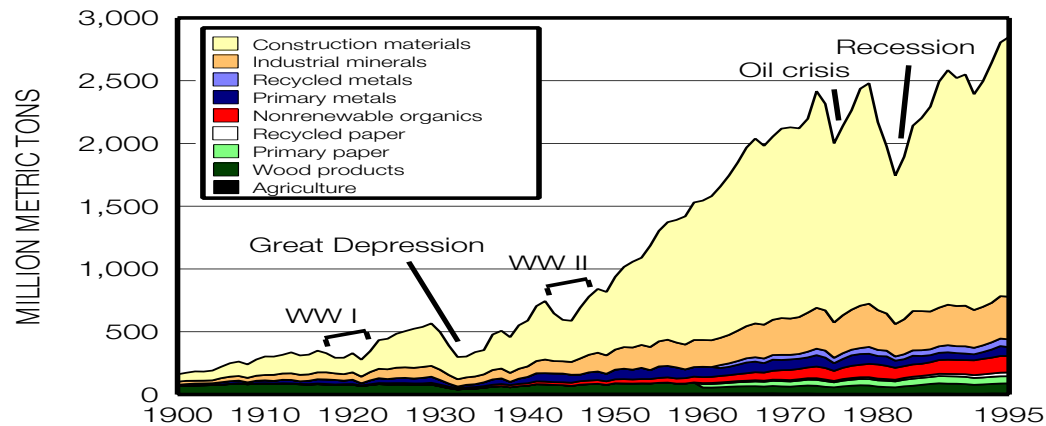
# Appendix

## a. Statistics

### 》労働生産性の推移



a.1 Labor productivity in Japan from 1994 to 2013.  
(Japan Federation of Construction Contractors, 2015).  
Green: All industries  
Blue: Manufacturing industries  
Red: Construction industry



a.2 Amount of raw materials consumed in the United States from 1900~1995 (Matos & Wagner, 1998).

Rank	City	Price To Income Ratio	Gross Rental Yield City Centre	Gross Rental Yield Outside of Centre	Price To Rent Ratio City Centre	Price To Rent Ratio Outside Of City Centre	Mortgage As A Percentage Of Income	Affordability Index
1	Jakarta, Indonesia	23.78	6.47	6.56	15.44	15.25	303.14	0.33
2	Bandung, Indonesia	20.83	4.47	11.3	22.37	8.85	229.24	0.44
3	Bali, Indonesia	19.25	4.57	6.79	21.86	14.72	230.64	0.43
4	Surabaya, Indonesia	18.81	6.63	6.41	15.09	15.61	245.36	0.41
5	Medan, Indonesia	9.92	3.17	3.99	31.55	25.04	107.73	0.93

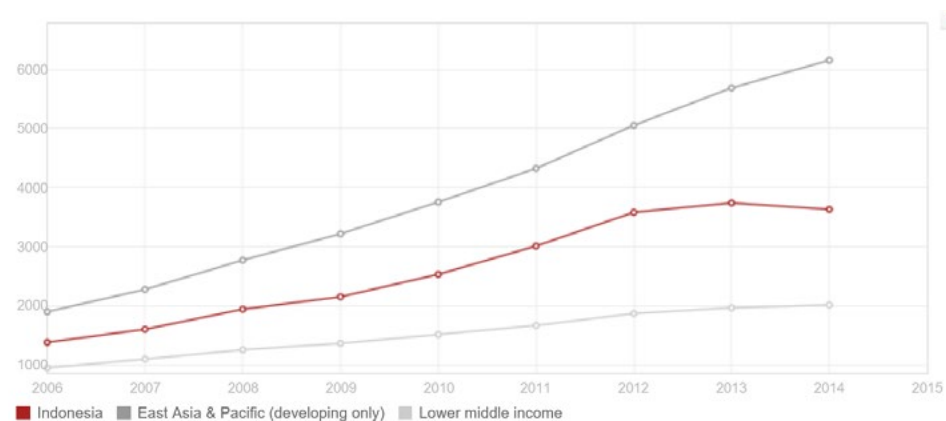
a.3 Affordability indexes of Indonesian cities in 2015 mid year. (Numbeo, 2015)

Year	Total Of Flats	Total Of National Housing
2008	805	5 216
2009	10	5 870
2010	1402	10 522
2011	316	9 675
2012	-	10 555

a.4 Number Of Flats And National Houshing Built in Indonesia (Unit). (Badan Pusat Statistik, 2015)

Household Groups	Average of Total Income		
	2000	2005	2008
Agricultural Labour Household	2 291.7	4 634.0	5 986.0
Agricultural Entrepreneur Household	18 018.3	6 876.4	11 420.1
Operator, Landowner of 0,0- 0,5 ha agricultural household	2 617.6	5 304.3	
Operator, landowner of 0,5- 1,0 ha agricultural household	3 922.0	8 011.2	
Operator, landowner of > 1,0 ha agricultural household	5 504.7	11 279.5	
Non-agricultural low income level rural household	3 772.9	8 642.3	13 421.8
Non-Labour force rural household	4 843.7	9 528.8	15 039.8
Non-Agricultural high income Level Urban Household	7 800.7	16 594.1	29 203.8
Non-Agricultural Low Income Level Urban Household	5 929.0	11 083.2	18 768.9
Non-labour Force Urban Household	6 854.9	11 623.4	19 580.4
Non-Agricultural High Income Level Urban Household	10 657.0	23 122.0	40 889.1

a.5 Average of Perkapita Total Income by Household Group (Thousand rupiahs) (Badan Pusat Statistik, 2015).



a.6 GNI per capita, Atlas method, Indonesia (The World Bank, 2015).

## b. Affordable housing

### b.1 Holcim affordable housing: Solusi Rumah

#### Description

While by convention Indonesian homes are built and renovated in a gradual way using small amounts of cement, Solusi Rumah sells pre-cast concrete elements, a much more cost-efficient method. It offers a one-stop solution to the Indonesian home builder.

#### Features:

By using the Solusi Rumah software the customers can accurately calculate material costs in real time.

Families with a basic monthly income of US\$ 150 have access to a 21m<sup>2</sup> to 65m<sup>2</sup> home at the cost of approximately US\$ 120/m<sup>2</sup>.

A variety of affordable house designs is available. They allow for future expansion and can be tailored to the customer's needs.

Any of the trained masons of Holcim Indonesia's network can build an affordable house in less than four weeks.



Content retrieved from <http://www.holcim.com/media-relations/our-major-projects/solusi-rumah-affordable-housing-in-indonesia.html>

## b.2 Habitat for Humanity: in Indonesia

### Description

Habitat for Humanity Indonesia builds, rehabilitates, and repairs simple, decent homes with the help of home partner families, volunteer, and donations of money, materials, and other gifts-in-kind.

### Features:

Different types of building including: new house construction, house rehabilitation/repairation, and community facilities such as multifunction room, playground and library, public toilet and water facilities

Up to January 2013, HFH Indonesia has served more than 39,000 families; which provide a decent shelter for more than 140,000 people spread out in 59 sub-districts in 13 provinces

On general scale, the total cost of a basic new home is IDR 25,000,000. However, the cost for every house is different and depends on the location (province), labor, the material costs, and other expenses.



Content retrieved from <http://habitatindonesia.org>



### b.3 Indonesia national affordable housing company: PERUMNAS

#### Description

PERUMNAS is the national housing company founded since 1974 in Indonesia. Although with limited amount of housing provision, it continues to provide affordable houses for middle-to-low income groups. With the launch of the one-million-home project PERUMNAS has been gaining more financial support to expand its housing provision.

#### Features:

PERUMNAS in Bandung sells houses from 34m<sup>2</sup> to 90m<sup>2</sup> with the range of price from 87MRp. to 478MRp.

It declared a target of building 100,000 homes / year in 2010~2015.

With increasing support from the government housing project, more finance is offered to construct more affordable housing.



Content retrieved from <http://perumnas.co.id/produk/>

## c. Modular housing

### c.1 Champion Home Builders Inc.

Champion Home Builders Inc. is an American modular housing company that provides a wide variety of factory-built solutions from single-family and multi-family modular homes, to commercial and government buildings.

#### Customization

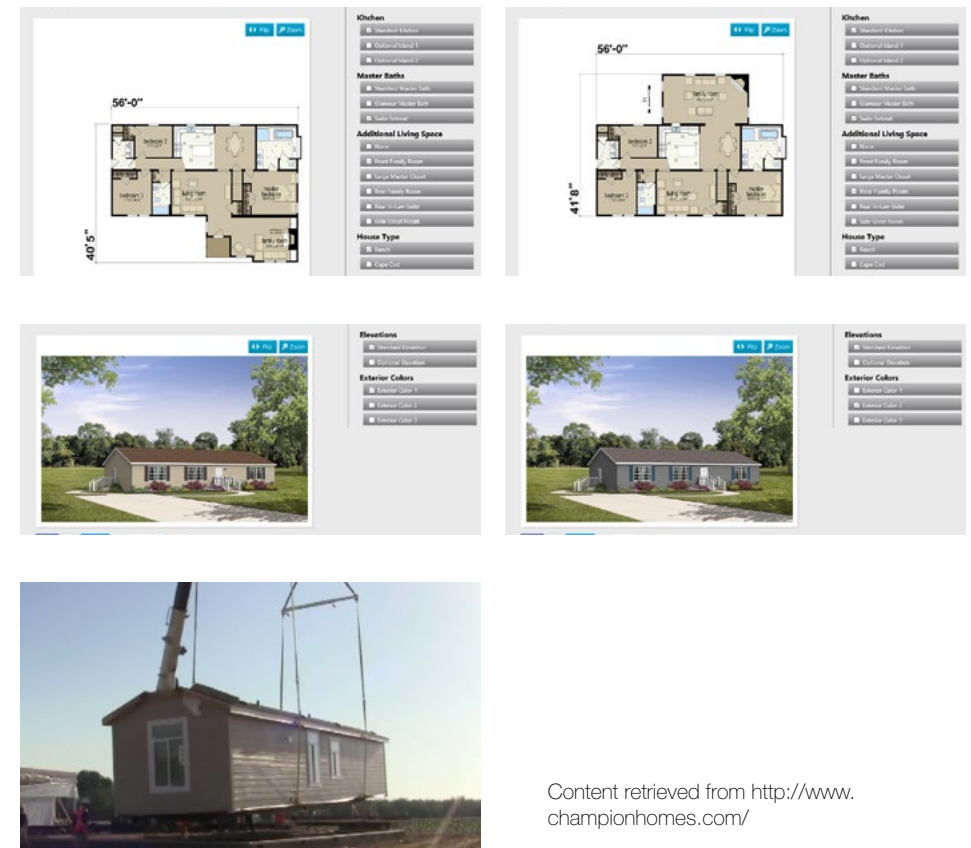
The modularity of the product offer a variety of design options for the customers. The customer can chose the variation of plans and their preferred finishing. The company also offer more personalization options if it is required.

#### Construction

In construction, each building module is prefabricated in the factory, and assembled with crane on site.

#### Limitation

The variation of design is still predetermined. The prefabricated modules would need large transportation space.



Content retrieved from <http://www.championhomes.com/>

c.2 Livinghomes, LLC.

Champion Home Builders Inc. is another American modular house company. Unlike champion Homes, this company provides more modern design. However, the options for building layout seem to be fewer.

#### Custionmization

Although with fewer options for layout, they provide lots of options for other elements such as finishing, installation, system etc.

#### Construction


It uses a similar way of construction as Champioin Homes.

#### Limitaion

Same as Champion Homes, and too limited in terms of layout, only predetermined layout can be chosen.

### C6/CK Series LivingHomes


The lowest cost LivingHomes. Designed by LivingHomes.  
[About the C6/CK](#)



**C6.1**  
[Explore](#) [Configure](#)

3 bedrooms, 2 baths  
1,288 sf  
42' w x 30' d x 12' h  
base: \$179,000  
complete: \$275,000

### CK4




**CK4**  
[Explore](#) [Configure](#)

3 bedrooms, 2.5 baths  
1,690 sf - 2,008 sf  
205 sf decking  
24' w x 52' - 64' d x 23' h  
base: \$245,000  
complete: \$424,000

### Ray Kappe LivingHomes

The epitome of modern, sustainable living.  
[About Ray Kappe](#)




**RK1**  
[Explore](#) [Configure](#)

4-5 bedrooms, 2.5-3.5 baths  
2,560 sf - 3,100 sf  
1,435 sf decking  
40' w x 44' - 60' d x 34' h  
base: \$665,000  
complete: \$950,000

### KieranTimberlake LivingHomes

Great designs for single or multi family.  
[About KieranTimberlake](#)



**KT1.3**  
[Explore](#) [Configure](#)

1 - 3 bedrooms  
1,858 sf  
22' w x 40' d x 40' h  
\$145/sf  
starting at \$269,000

EXPLORE

CONFIGURE

MY VIRTUAL HOME

3 bedrooms, 2 baths  
1,288 sq ft, 0 sq ft decking  
42' w x 30' d x 12' h

COSTS

BASE PRICE  
\$179,000  
OPTIONS  
TOTAL BASE & OPTIONS  
\$179,000  
\$139 / sq ft

LEED PLATINUM GOLD BUILT CERTIFIED

96

LOG IN / REGISTER TO SAVE AND SHARE

Create your own LivingHome.

Click on each step and make your selections. Some options impact your LEED points and others cost additional money. You can save and share your LivingHomes with others.

1 Exterior

2 Interior

3 Bathrooms


4 Bedrooms

5 Laundry Room

6 Systems

7 Site and Landscaping

Start



Content retrieved from  
<http://www.livinghomes.net>

### c.3 Gluck+ : The Stack

The Stack is a project done by Gluck+ which addresses the need for moderate-income housing in Manhattan. It is seen as a pilot project for developing a quality and economically viable housing solution to strategically rebuilding and filling gaps in outmoded housing infrastructure in the city.

#### Customization

Although not intended, this project does have the possibility to adapt to different needs. By using similar size modular units, limitless combination can be achieved.

#### Construction

Same as the previous two. Prefabricated and mounted with crane on site.

#### Limitation

A very critical issue is pointed out in their webinar: although the use of prefabrication reduces the cost (because of stable environment, and less waste of material), the total cost of the building is almost the same as traditional ones. The reason is that each module needs its own structure to be operated, which is extra, and the interfaces also doubles. When a multitude of modules come together this drawback gets worse than usual.



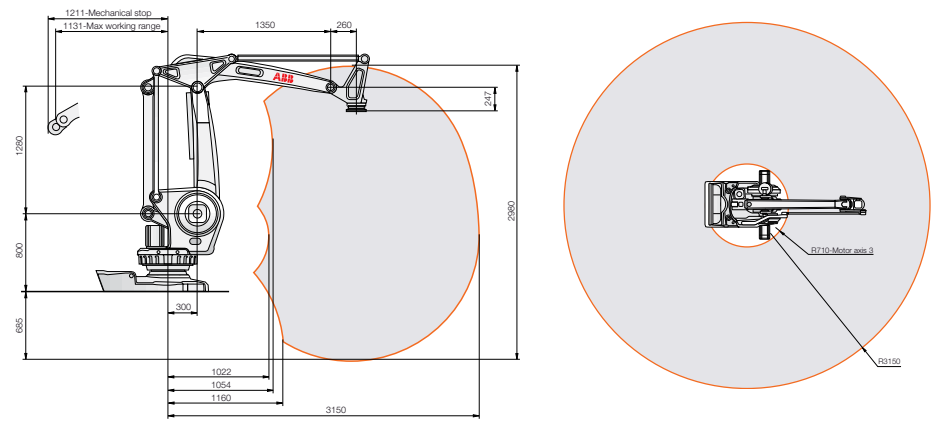
Content retrieved from <http://gluckplus.com/project/the-stack>

d. Robot & Machine

d.1 Specifications of some current Industrial robot products, content retrieved from <http://www.abb.com/>

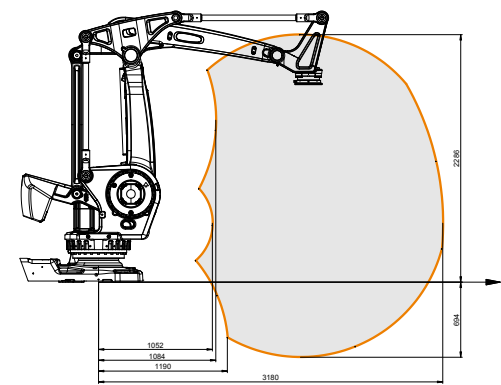
IRB 660

Specification		
Robot versions	Handling capacity	Reach
IRB		
660-180/3.15	180 kg	3.15 m
660-250/3.15	250 kg	3.15 m
Number of axes:	4	
Protection class:	IP 67	
Mounting:	Floor mounted	
IRC5 Controller variants	Single cabinet, Dual cabinet	



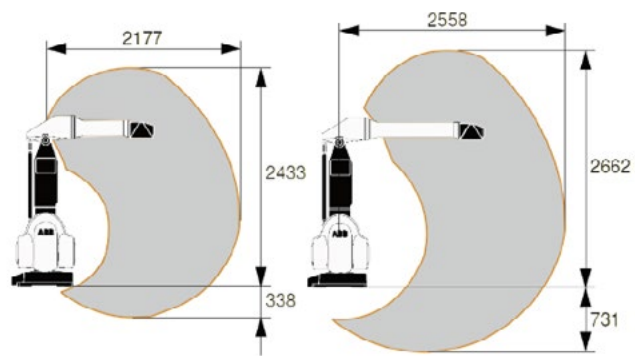
IRB 760

Main applications	
Full layer palletizing, palletizing, depalletizing, material handling	
Specification	
Handling capacity	450 kg
Reach	3.18 m
Number of axes	4
Protection	IP67
Mounting	Floor
IRC5 controller variants	Single cabinet, Dual cabinet



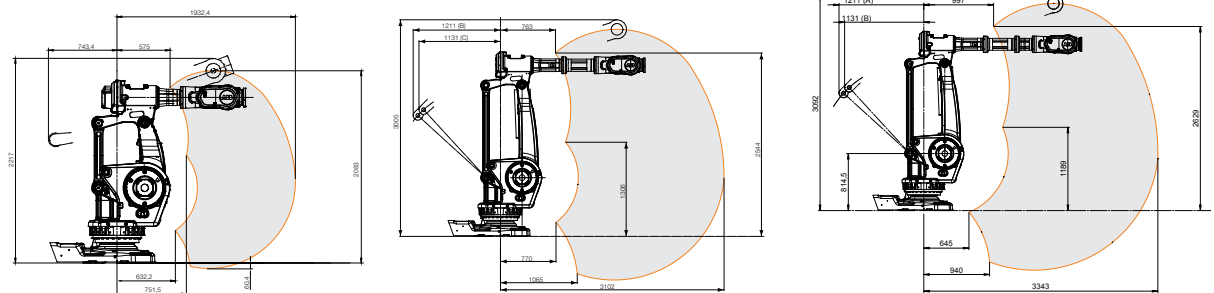
IRB 580

Specification	
Number of axes	6 axes. 7 when rail-mounted
Payload on wrist	10 kg
Robot mounting	Floor, inverted and rail
Ingress protection degree	IP67 (wrist IP54)



IRB 6660

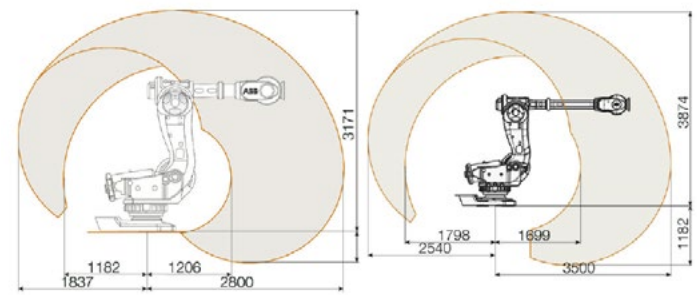
Specification			
Variants	Reach	Payload	Armload
IRB 6660-100/3.3	3.35 m	100 kg	20 kg
IRB 6660-130/3.1	3.10 m	130 kg	20 kg
IRB 6660-205/1.9	1.93 m	205 kg	15 kg + 500 kg on frame
Number of axes:	6		
Protection	Complete robot IP 67, Optional FoundryPlus 2 and chip protection (only IRB 6660-205/1.9).		
Mounting:	Floor mounted		
IRC5 Controller variants	Single cabinet, Dual cabinet		





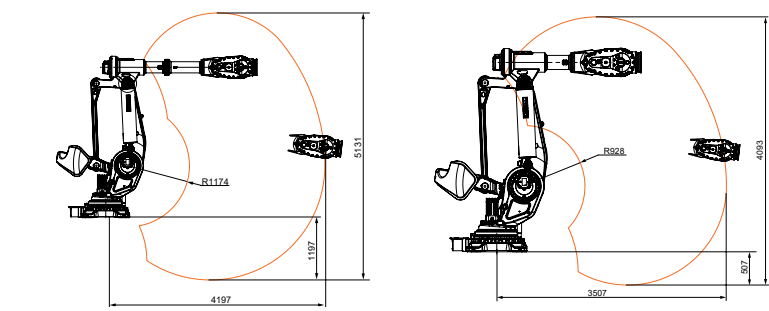
IRB7600

Specification				
Robot versions	Reach	Handling capacity	Center of gravity	Max. wrist torque
IRB				
IRB 7600-500	2.55 m	500 kg	360 mm	3010 Nm
IRB 7600-400	2.55 m	400 kg	512 mm	3010 Nm
IRB 7600-340	2.8 m	340 kg	360 mm	2750 Nm
IRB 7600-325	3.1 m	325 kg	360 mm	2680 Nm
IRB 7600-150	3.5 m	150 kg	360 mm	1880 Nm
(IRB 7600-150 loaded with 100 kg 1660 mm)				
Extra loads can be mounted on all variants				
50 kg on upper arm and 550 kg on frame of axis 1.				
Number of axes:	6			
IRC5 controller variants:	Single cabinet, PMC			



IRB 8700

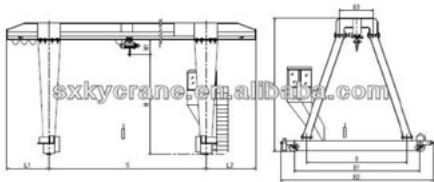
Specification				
Robot versions	Reach	Handling capacity	Center of gravity	Wrist torque
Without Lean ID				
IRB 8700-800/3.50	3.50 m	800 kg	460 mm	6043 Nm
IRB 8700-550/4.20	4.20 m	550 kg	460 mm	5279 Nm
With Lean ID				
IRB 8700-800/3.50	3.50 m	630 kg	460 mm	6043 Nm
IRB 8700-550/4.20	4.20 m	475 kg	460 mm	5279 Nm
Extra loads can be mounted on all variants.				
50 kg on upper arm and 500 kg on frame of axis 1.				
Number of axes	6			
Protection	Complete robot IP67			
Mounting	Floor mounted			



d.2 Specifications of some current gantry crane products, content retrieved from <http://www.alibaba.com/>

Keliyuan MH type cantilever gantry crane

Capacity	T	3	5	10	16	20
Operational method		Pendent line with push button /cabin				
Speed	Lifting	m/ min	8 ,8/0.8	8,8/0.8	7,7/0.7	3.5
	Cross travelling		20	20	20	20
	Long travelling		20	20	20	20
	Ground Cabin		30,40	30,40	30,40	30,40
Electric hoist	Type		CD1/MD1	CD1/MD1	CD1/MD1	CD1 HC
Lifting height	m		6,9			
Working duty			A5			
Power supply			380V 50HZ 3phase AC			
Span	m		12	16	20	24 30



Keliyuan MH type cantilever gantry crane

Capacity	T	1	2	3	5	10
Operational method		Pendent line with push button /cabin				
Speed	Lifting	m/min	8 ,8/0.8			
	Cross travelling		20			
	Long travelling		30			
Electric hoist			CD1/MD1			
Lifting height	m		6	9	12	18 24
Working duty			A3-A5			
Power supply			380V 50HZ 3phase AC			
Span	m		7.5~31.5			





d.3 End effector types, and specifications of some current products, content retrieved from <http://robotiq.com>, <http://www.abb.com>, <http://schunk.com>, <http://www.ati-ia.com>, <http://www.tregaskiss.com>

## Grippers

Grippers are the most common type of end effector. They can use different gripping methods and actuation styles. According to actuation styles, there are electric gripper, pneumatic gripper, hydraulic gripper and vacuum gripper.

Brands of robot grippers include Schunk, Robohand, PHD, SOMMER, Robotiq, ABB

### FlexGripper - Vacuum gripper

#### Main applications

Case palletizing

#### Specification

Handled products	1-5
Max. weight per lift	40 kg
Gripper weight	75 kg
Maximum product size (LxWxH)	1200 x 500 x 300 mm
Minimum product size (LxWxH)	240 x 240 x 100 mm
Number of zones	10
Cable rotation range	+ - 180°
Air pressure	4-6 bar
Handled pallet types	GMA/AUS/EUR/ISO



### Schunk Pneumatic gripper

#### 2-Finger Parallel Grippers

##### Miniature Parallel Gripper MPG and MPG-plus

- Gripping force from 9 N to 540 N
- Stroke per finger from 1 to 14 mm
- 10 sizes from 10 to 80
- For small and medium-sized components for assembly



##### Gripper for small components KGG

- Gripping force from 45 N to 540 N
- Stroke per finger from 10 mm to 60 mm
- 7 sizes from 60 to 280
- Thin gripper with robust T-slot guidance



#### 3-Finger Centric Grippers

##### Gripper for small components MPZ

- Gripping force from 20 N to 310 N
- Stroke per finger from 1 mm to 5 mm
- 6 sizes from 16 to 45
- For small and medium-sized components for assembly automation



## Schunk Electric gripper

### 2-Finger Parallel Grippers

#### Intelligent Gripper EGP

- Gripping force up to 135 N
- Stroke per finger 6 mm
- Size 40
- Drive concept electrically, gripping force is adjustable in up to four steps



#### Intelligent Gripper EGN

- Gripping force from 170 N to 1000 N
- Stroke per finger from 8 mm to 16 mm
- 3 sizes from 80 to 160
- Gripper with servo motor
- Pre-positioning capability to reduce cycle times



### 3-Finger Centric Grippers

#### Intelligent Gripper EZN

- Gripping force from 500 N to 800 N
- Stroke per finger from 6 mm to 10 mm
- 2 sizes from 64 to 100
- Gripper with servo-motor
- Pre-positioning capability to reduce cycle times



## Schunk Hydraulic gripper HZN 125

#### Medium:

Hydraulic oil, filtered (10 µm) viscosity 46 mm<sup>2</sup>/s at 40 °C according to ISO VG, max. temperature 60 °C

#### Operating pressure range:

from 30 - 60 bar

#### Repeat accuracy:

HZN 80 and HZN 100 approx. 0.05 mm, HZN 125 and HZN 160 approx. 0.1 mm

#### Pressure connections:

either on the sides or the base.

It is essential that you use a flow control valve set to 2 l/min.

#### Maintenance:

permanently lubricated, re-lubrication recommended after 1.5 million strokes

#### Method of functioning:

positively guided wedge hook system



### Force-Torque Sensors

Force-torque sensors (FT sensors) are pucks installed between the robot flange and the tool that interacts with the part. They measure the force and torque that the robot applies to the part through the tool. FT sensors are used when the force that the robot applies need to be controlled.

Brands of force-torque sensors include ATI, JR3 and Robotiq.



### Material Removal Tools

This category includes cutting, drilling and deburring tools installed as robot tools.

Brands of robot cutting tools include ATI and RAD



### Welding Torches

Welding is a very popular robotic application (takes up 29% of robotics use). Welding torches have thus become very efficient end effectors that can be controlled in a sophisticated way for optimized welding. Some torches also come with wire feeder for an even better control of the process.

Brands of robot welding torches are Tregaskiss, Binzel, SKS and Fronius.



### Tool Changers

Tool changers are used when many different end effectors need to be used in sequence by one robot. They are used to standardized the interface between the robot flange and the base of the tool. They can be manual or automatic.

Brands of tool changers are ATI, RAD, Applied Robotics and De-Sta-Co.



## e. Robotic construction system

### e.1 EU Futurehome Project (Balaguer, 2003)

The EU FutureHome project focuses on the development of new modular building construction with several important features: high quality, variety of designs, mass production, reasonable cost, and etc.

The main objective of the FutureHome project is the development of Integrated Construction Automation (ICA) concept and associated to them technologies during all the stages of the house-building construction process.

#### Modularity

The building consists of 3D and 2D modules. 2D modules are enclosure panels, which also contains doors and windows. 3D modules are composed of 2D modules, beams and installation, and are assembled on site to form a complete building. A special connector between 3D modules is designed to solve the tolerance issues.

#### Robotics

The robotic system is a robotized overhead crane with a specially designed gripping system that fits the special connectors.

#### Design

The different types of modules forms a catalog for design. Design is then able to be broken down into specific combinations of modules. In this way design can be easily be communicated and quickly be generated.



Content retrieved from "EU FutureHome Project Results" (Balaguer, 2003)

## e.2 Automated construction by contour crafting (Khoshnevis, 2004)

This is a system researched by Khoshinevis that features the use of the specially designed end effector - a nozzle that ejects self supporting and fast drying concrete - that "prints" the concrete structure of a house.

### Modularity

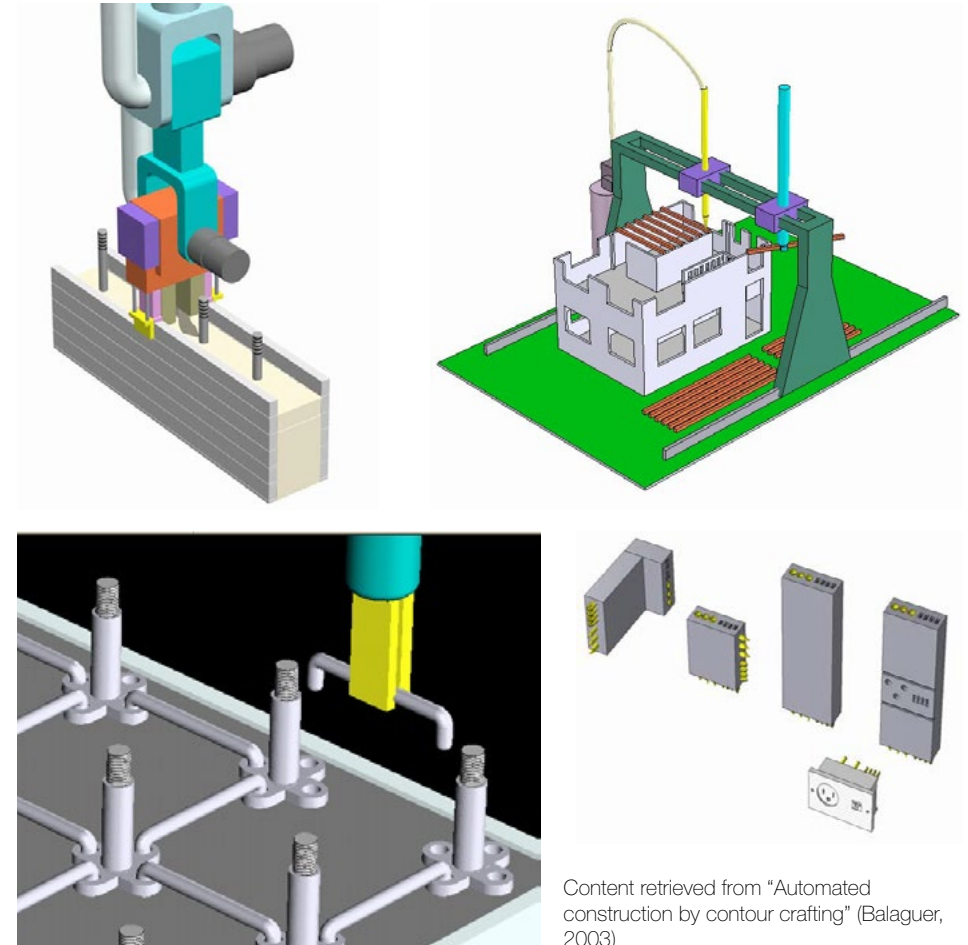
Since the structural concrete wall can be printed in any layout, there is no modularity in this aspect. However, for pipes and wires, special connectors designed for ease of robotic operation.

### Robotics

The key issues of this project lies in the design of the special concrete and the nozzle that ejects it. On top of that, a gantry robotic system is designed to operate the nozzle and other end effectors that connect the equipments. Also for other cases such as high rise, a gantry system that has self-climbing ability is designed.

### Design

Because of the relatively high freedom of contour crafting, lots of configurations can be achieved. There is still limitation however. The resolution needs to be relatively low to gain high speed, which leads to relatively low finishing quality. Also there is limitation on the minimum dimension of concrete elements.



Content retrieved from "Automated construction by contour crafting" (Balaguer, 2003)

### e.3 Big Canopy (Obayashi Corporation)

Big canopy is a system developed by Obayashi corporation for automated reinforced concrete high-rise construction. It is part of Obayashi's automation construction program. Another project is ABCS (Automated building construction system) for steel high rise.

#### Modularity

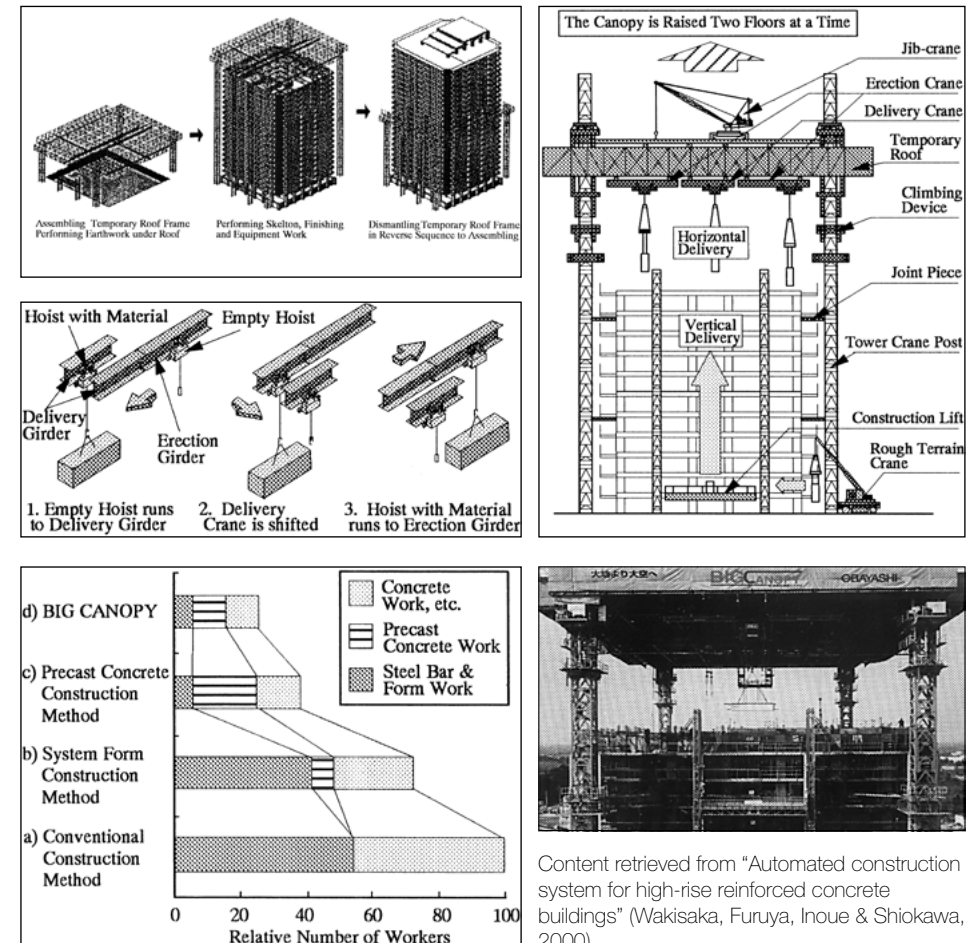
The system uses standardized precast reinforced concrete beams, column and floor slabs as construction elements.

#### Robotics

The system is basically a big gantry system with climbing mechanism. Each time the system finish construction of one floor, it "climbs" on top of its structure and begin construction of the next floor. New elements are fed to the system through a construction lift in/outside the building. A hoist exchange mechanism is applied for higher flexibility of object handling.

#### Design

This system is specially designed for high-rise. The main structure needs to be continues for the system to climb, and there is not much variation in plan layout. Since the system itself is very complicated, only high-rise with certain amount of levels can benefit from this type of system.





#### e.4 ABCS (Automated building construction system) (Obayashi Corporation)

ABCS is very similar to Big Canopy. The main difference is that they are for different structure types: Big Canopy for RFC high-rise, and ABCS for steel high-rise.

##### Modularity

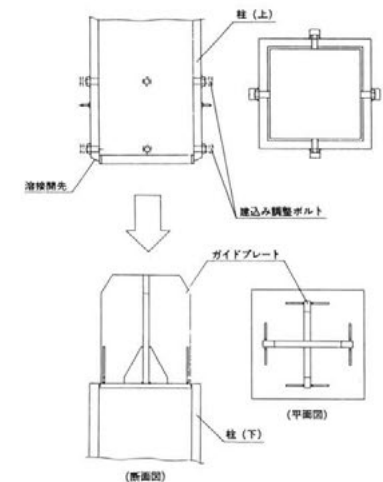
The system uses standardized steel beams, column and floor slabs as construction elements. One thing to mention is that the connection between elements are specially designed to compensate for the tolerance (using chamfer as guiding geometry).

##### Robotics

Similar to Big Canopy.

##### Design

Similar to Big Canopy.



Content retrieved from "Development of an Automated Building Construction System" (Shikawa, Ohkawa, & Mori, 1994)

e.5 SMAS (Solid Material Assembly System) (Kodama, Yamazaki, Kato, Iguchi, & Naoi, 1988)

SMAS is a system developed by researchers in Science University of Tokyo. It uses a block system for structure, and mainly suits smaller scale buildings.

#### Modularity

The strategy this project took is to compose the building with standardized reinforced building blocks. Although there are different types of blocks to meet different requirements of use, they can be joined because of their share connection interface. In fact, the blocks themselves do not bear the main weight. Concrete needs to be pour in from top of the constructed wall to make it stabilized.

#### Robotics

The main manipulator is a 6-DOF robotic arm. In real construction, however, the manipulator can be mounted to rails to extend its work range i order to finish larger project.

#### Design

The building can be designed in a similar way to conventional buildings, but always using a certain modules which is the size of the standardized block.

Articulated Robot

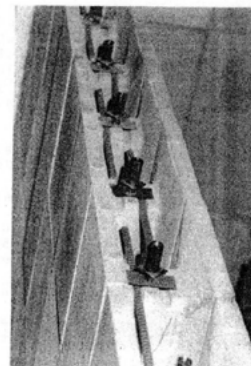
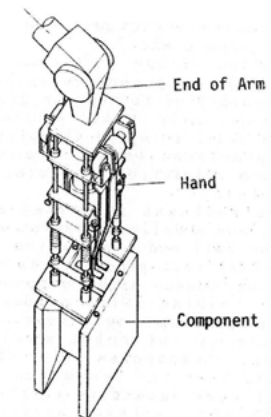
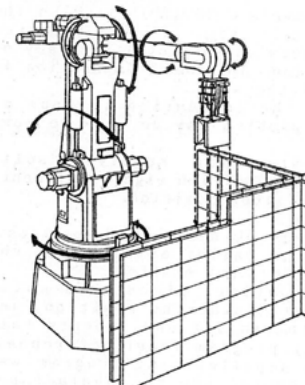


Fig. 2 Over-lapped Steel Bars for the Reinforcement

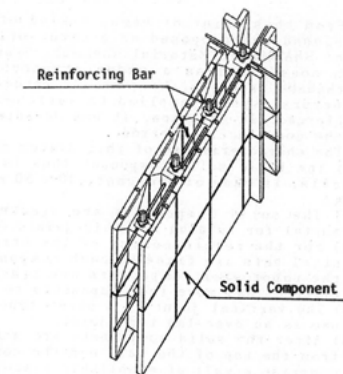


Fig. 3 Overview of Stacked Wall

Content retrieved from "A robotized wall erection system with solid components" (Kodama, Yamazaki, Kato, Iguchi, & Naoi, 1988)



## f. Miscellaneous

### j.1 Standard Container Specifications

	(8ft)	(10ft)	(20ft)	(30ft)	(40ft)
Container Length	2.42m	3.05m	6.06m	9.12m	12.19m
Container Width	2.17m	2.44m	2.44m	2.44m	2.44m
Container Height:					
Standard	2.26m	2.59m	2.59m	2.59m	2.59m
High cube		2.89m	2.89m	2.89m	2.89m
Internal Length	2.28m	2.80m	5.87m	8.93m	12.00m
Internal Width	2.10m	2.33m	2.33m	2.33m	2.33m
Internal Height:					
Standard	2.04m	2.35m	2.35m	2.35m	2.35m
High cube	-	2.65m	2.65m	2.65m	2.65m
End Door Aperture Width:	2.09m	as req.	2.28m	2.28m	2.28m
End Door Aperture Height:					
Standard	1.94m	as req.	2.26m	2.26m	2.26m
High cube	-	as req.	2.56m	2.56m	2.56m
Floor area	4.78m <sup>2</sup>	6.69m <sup>2</sup>	13.93m <sup>2</sup>	21.09m <sup>2</sup>	28.33m <sup>2</sup>
Cubic capacity:					
Standard	9.28m <sup>3</sup>	15.89m <sup>3</sup>	32.85m <sup>3</sup>	49.84m <sup>3</sup>	66.83m <sup>3</sup>
High cube	-	17.84m <sup>3</sup>	37.09m <sup>3</sup>	56.21m <sup>3</sup>	75.32m <sup>3</sup>
Weight	1.02 tonnes	1.52 tonnes	2.44 tonnes	3.25 tonnes	4.06 tonnes

