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## 1 Introduction

The objective of this paper is to delineate the development trajectory of IFD technologies. The paper starts with introducing the main theoretical views regarding innovation and technological regimes (i.e. socio-economic factors as well as technological and scientific principles that jointly shape the direction in which technologies develop). Next the recently proposed quantitative methodology for technological trajectory mapping (TTM) will be introduced. This is followed by an overview of the development of IFD systems in historical perspective as decribed in literature. The results of the application of the TTM methodology to investigate the development trajectory of IFD building systems in the construction industry will be presented thereafter. The paper ends with concluding remarks on the development trajectory of IFD systems by combining the results of the explorative historical and descriptive analyses of the IFD systems development with those of the TTM exercise.

## 2. Technological Trajectory Mapping Methodology (TTMM)

Over time production processes evolved from home-based hand manufacturing via extensive changes of production characteristics from mechanization, rationalisation, systematization, standardization and automatization in a sequence of era towards large-scale factory production -bringing about a number of economic advantages- thanks to *technological innovations*. Innovations (problem-solving activities by firms) take place in a certain knowledge environment (*Technological Regime(TR):* which are socio-economic factors as well as technological and scientific principles that jointly shape the direction in which technologies develop socio-economic factors as well as technological and scientific principles that jointly shape the direction in which technologies develop. It sets the boundaries and form a constraint to what can be achieved in innovative activities associated with a given set of production activities, and the directions (natural trajectories) along which solutions are likely to be found [Marsili and Verspagen, 2001]. Sectoral asymmetries in industrial innovativeness can be interpreted on the grounds of *differences in TR* [Nelson and Winter (1982); Dosi 1982] Innovations follow a certain *development trajectory*, which is a stream of subsequent innovations as a result of continuous changes in paradigm and regimes.
To get a better understanding of the actual innovation trajectory Verspagen (2005) proposed -similar to Hummon and Doreian (1989)-. to use the *technological trajectory mapping methodology* (TTMM) to analyse the network of patent citations that are interconnected to identify the main stream of technological development. Patents are an indicator of a technological development and provide information on changes in the state of the art of a technology. The TTM methodology is a combination of patent citation analysis and literature study. The patent citation analysis technique is

based on the idea that knowledge flows via patent citations and these form a certain network. If a younger patent cites an older patent the idea is that the knowledge of the older patent is utilized by the younger patent.Once the network structure is clear it will be possible to say something about the importance of various individual connections between two patents in the network. The patent citation analysis is a pure analytical method, and consists of three sections; (1) the creation of datasets, (2) the descriptive statistics and (3) the delineation of the patent citation network. A patent citation network is seen as a collection of vertices (patents/ pieces of knowledge) and edges (connections between patents). A patent citation network is represented as a matrix C. in which the element $c_{ij}$ is equal to 1 if patent j cites I and zero otherwise [Verspagen 2005] The goal of the patent citation analysis is "to construct a 'main path' through the network that corresponds to the main flow of ideas in this field" [Hummon and Dorean 1989].A patent citation analysis does not give any further information on other factors that influence the development of a technology, such as the technological regime that either may stimulate or form a possible bottleneck. That is why the patent citation analysis is combined with a literature study on IFD building. The study described in this paper applied this methodology and investigated patent datasets in search for the main streams of technologies and knowledge regarding IFD building systems. Before describing the results of the patent citation analysis the results of a historic analysis of IFD building systems based on a literature study will be described.

## 3. Industrialised Flexible and demountable IFD building systems:

In the course of time building construction evolved from the application of simple mechanization on site via a further rationalisation and systematization of the construction process towards the prefabrication, standardisation, pre-assembly and modularisation of parts of the building, moving a large part of the building process from the site to the factory. Prefabrication reduces time-consuming on-site activities and increases on-site productivity; it has the possibility to contribute to a relatively low cost and standard quality of output and it eliminates some of the burdens of construction projects such as suboptimal site conditions. Prefabrication as such existed already in the ancient world (Egypt, Greece, Italy), where buildings were erected with prefabricated components made of stone [Warszawski 1990]. Industrialised building was pushed ahead after World War II by governments in Western Europe and Japan who acted as large clients faced with an extensive need for housing for millions of people in their countries.Industrialised building moved further forward through s*tandardisation* and m*odularisation. S*tandardized components -mass-produced in highly automated and strictly quality controlled production facilities to exacting physical properties and dimensions --fit together in a modular system of design, providing multiple preassembled units. A major problem arising from modularisation is in the connection of units of different modular dimensions. [Ricketts 2005]. The connection on site of the units is a distinct challenge. It is in this respect that efforts have been dedicated to develop innovative technological solutions such as specific joints and particular materials that allows the right fixation and connection of different prefabricated modular building elements. Prefabrication is often associated with mass production of buildings and thereby accused to neglect the clients' desire for individuality. Above that -in to today's ever-changing world, in which businesses and organizations understand the importance of being flexible, multifunctional and adaptable- clients of some types of buildings -such as office and health care buildings - expect that the buildings they occupy are flexible and adaptable too. Another aspect is that in general the life time of a building is expected to be approximately 60 years before the decrease of the functional, economical, sometimes socio-cultural value and in case maintenance is not up to standard also the technical value sets in. The life cycle of a building can be prolonged by thoughtful planning and design and engineering in such a way that a building can become highly versatile and adaptable to meet the client's needs for the present and the future. It all depends on the cost-effectiveness to maintain and up-grading the main structure and its infill whether the building is knocked down and disposed as waste material. An increased social pressure to improve the environmental sustainability of the generally rather poluting construction operations as well as government policies- legislation and subsidies- stimulated thinking about more sustainable building in a number of countries. It is in this perspective that the adaptability and sustainability aspect of buildings came into the picture. Solutions were sought in the development of *IFD building systems*. It should be noted however that these efforts are rather economically and practically driven than out of care for the environment.

From the above can be learned that the *Technological Regime* in which the construction industry is operating –the socio-economic environment with its rules, regulations, expectations and requirements- have changed, setting new boundaries for technological innovations. However IFD technologies are still waiting for a real breakthrough. The market demand for IFD buildings is most often limited to a demand for temporary buildings or modules. The client's perception of these buildings is that of a lower quality and inferior compared to traditionally built ones although the outside of the building may even look the same.[Hermans 1997]. The present legal instruments to implement policy also do not work in favor of IFD in many countries. The legislation for IFD building is the same as for traditional building but IFD buildings are classified as temporary [Gurchom 2002; Hermans et all 1997; http://www.ifd.nl 2006] National policies, although meant to stimulate IFD building, do not work out as desired in a number of cases –e.g. the Netherlands- due to a lack of communication between the construction professionals and policy makers.[Gurchom 2002] Design and building principles changed slowly. Moreover the introduction of prefabrication in the construction process tends to make the total process more complex. The requirements on dimensional tolerances are more severe. It requires more co-operation and co-ordination within the design and also construction processes should change including more transparent forms of planning cooperation and new forms of communication and/or exchange between planners and builders. [Koskela et all 2000]. A real move towards IFD building requires a regime shift in the construction industry. [Egmond 2005].

## 4 Empirical findings

The TTMM has been applied for the analysis of the technological "trajectories" of IFD systems'The US Patent and Trademark Office (USPTO) database (online full-text patents back to 1976) was used to search for a *set of patents* on IFD technologies by means of different queries with a number of keywords.The goal was to get between 1000 and 1500 valid patents, which are needed for the rest of the research. Two separate datasets were constructed. The first search with queries led to 1498 hits on the USPTO website which showed that the most patents belong to patent class 52/79.1 and its subclasses. Class 52/79 includes preassembled sub-enclosure or substructure section(s) of a unit or building [USPTO 2006]. Keywords used were prefab; prefabricated; pre-manufactured;temporary; modular; standardized; elements; modules; structures; building; wall; floor; roof. We refined this database by including other keywords such as industrial, window, joint, door, and excluding electrical. This led to 1150 hits. Next we searched for the citations that these patents make to other patents, by using the dataset of the National Bureau of Economic Research (NBER) with data between 1976 and 2002.

The 1150 patents of the refined query dataset appeared to be divided in 560 patent subclasses, which indicate that the IFD technology includes several types of technology. Most of these classes only contained 1 patent. There is a large distribution of the classes with more than 4 patents. The company analysis resulted in 605 different companies holding patents in the dataset. The company that holds the most patents only has 10 IFD technology patents. The conclusion is that no company is a real leading innovating company regarding IFD technologies and seemingly companies are not collaborating too. These findings reflect the fragmented character of the construction industry.

By using the Search Path Link Count (SPLC) method, the main paths of the development trajectory of a patented technology in the patent network was calculated. [Verspagen 2005]. The top main paths in the network are supposed to indicate the most important and interconnected patents and their development trajectory. To be able to distinguish which type of technology is mainly patented within the main development trajectory and which level of technological complexity is reflected in the patents, we have classified IFD technologies based on different levels of complexity. (1). *Construction components* -the parts used to create different elements, like joints or the frames in a wall-element; *(2) Elements* - the parts used to create a module or a building.(e.g. a panel, a partition wall, a roof or floor); *(3) Modules*, - a unit, a module or a building; (4) *A process* for making the components, elements or modules; (5) *Other or non-relevant* patents.

The *main paths of both datasets* represent only a rather low percentage of the total datasets (218 patents :15% in the 52-79 dataset and 64 patents :5% in the refined dataset). This means that there are no real strong interconnetions between the patents. The large fragmentation in the building sector could be due to that different producers of building products create their own technological trajectory with their own technological innovations which are not compatible with other technologies of other producers and that these technologies are not based on older technologies from different companies. A closer look at the type of patented technology that is included in the first main path of the class 52-79 dataset shows that 54% of the patents in this 1st main path are those for building elements and 33% for modules. In the *2nd, 3rd* and *4th* main paths –all together 164 patents- most of the patents are for modules. With regard to the refined query dataset the 1st main path represented 5% of the patents of which the majority are patents for module technologies, 19% patents for building elements and 16% for process technologies. The 2nd and 3rd main path for this dataset however include for more than 50% patents for building elements.

*The first top main path* of the 52-79 dataset includes 20 patents for innovative modules and buildings. The innovative technologies developed from a general technology of modular and prefabricated building systems, towards more specified patents which explain a more detailed and specific version of the technology. The second top main path includes 13 patents. This trajectory of patents develops from basic patents – such as a method of building construction using synthetic foam material and a Prefabricated building module and modular construction method for the module - to more specific patents for modular building technologies such as a Standardized portable housing unit, Mobile home and a Portable refrigerated storage unit.

The *top main path of the refined query data set* consists of in total 11 patents representing mainly patents for building elements such as wall systems to separate spaces into different parts in several ways highly reflecting the flexibility issue of IFDbuilding. The patented technologies include those in the following sequence: a Wall system; Partitioning system; Office paneling system; Space divider system; Display wall formed of readily attachable and detachable panels; Work space management system; Free standing modular furniture and wall system; Wall panel system; Clean room wall system. Compared to top main paths in other sectors the top main paths for IFD technologies are relatively short.

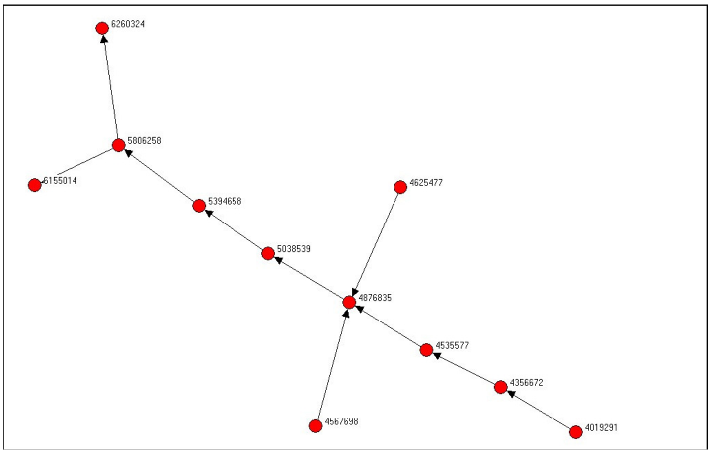


**Figure 1. Top main path refined query dataset**

The development trajectory of IFD building technologies over time appeared to proceed rather slowly. In contrast to developments in other sectors, such as the ICT sector for example only once a year and sometimes even only once every two years a new patent is added to the trajectory. Still one can notice a learning curve in the development trajectory of the patented technologies. A most significant aspect is that after 1998 the development trajectory shifts towards another dominant direction and even introduces a new top main path in the year 2002.

## 5. Conclusions

What could be learned from the study with the TTM methodology is that indeed patented technologies are based on knowledge and insights gained from foregoing innovations so there is a certain learning curve noticable also in construction. However this is in contrast to the trajectories in other sectors obviously rather limited. There certainly is no organized technological development of IFD technologies. The TTM analysis showed that there is an absence of one or even a set of

companies that can be seen as the leading innovating ones in the field of IFD technologies. There is only a relatively small number of top main paths, which on their turn are relatively short. This indicates the variety in different types of IFD technologies that are developed. If any, the focus in the innovative efforts can be seen in the development of different building elements inlcuding the materials to be used in IFD building systems as well as in the development of modular building systems. So there is no clear single direction in which the IFD technologies are developed. The characteristics of the technological trajectory confirm the rather diffuse character of the construction industry in which many different actors work on a diversity of innovations regarding IFD building systems. Despite the fact that IFD technologies have gained more interest among construction professionals being aware of the advantages of industrialised building and the social pressure to achieve more sustainable construction practices whilst meeting the customer's demand for higher quality at lower costs, the concept of IFD technologies is still rather young and waits for a real breakthrough. A number of bottlemecks to be found in the Technological Regime of the Construction Industry –as mentioned in section 3 of this paper- are due to this.
The technological trajectory methodology that is applied gives a useful though no comprehensive understanding of the mechanisms at work regarding the development and adoption of IFD building systems. A combination of historic and descriptive analyses by using the evoluationary network theories gives a better understanding and opportunity to utilize the potential offered by innovative IFD building systems to push the construction industry performance into the desired direction.

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