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Fixed capital investment estimation for modular production plants

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ABSTRACT

Modular plant design is an approach for making chemical production more flexible and more efficient. Different approaches for modular plant design have been developed, for example in the CoPIRIDE or F³ factory project. They have in common that reductions in design and construction expenses for modular equipment and its assembly are expected e.g. by preassembly of modules in a workshop under controlled conditions resulting in less field work on the construction site for erection. However, the main disadvantage of the modular approach is the loss of economy of scale. Thus, the effective impact of the modular concept concerning the fixed capital investment has to be investigated. In this article, a new approach for estimating fixed capital investment of modular production plants will be presented and applied using a generic example. Based on the results we expect that positive effects through modularization on engineering and construction costs can nearly compensate the loss of economy of scale. In the investigated example investment costs of the modular plant are 12% higher than for the comparable conventionally built plant. Such increase could allow other effects that are attributed to the modular concept to be employed to advantage. That would be an economic improvement and a reduction of investment risk in view of the modular plant's life cycle.

1. Introduction

Future development of global chemical market is characterized by diversification and fragmentation; technological improvements and new fields of application lead to an increasing demand for more specific products and thus, to an increasing number of products, decreased production volumes for the individual product, delocalized product demand and shorter product life cycles. Results of this are more volatile markets and the need for a more flexible production (Buchholz, 2010). Additionally, raw material prices are subject to fluctuation and companies are forced to pass on price declines in raw materials, resulting in decreasing margins and moderate growth (Bünger, 2016). To keep up with this development, chemical production needs to become more flexible and more efficient on the long run.

Fulfillment of both, flexibility and efficiency is hardly possible applying existing production concepts as plants are either designed to work highly efficient at a single operating point (e.g continuously operated large-scale plants (Buchholz, 2010; Lier et al., 2015)) or to enable a high degree of flexibility while losing efficiency (e.g. multi-purpose batch plants (Lier et al., 2015; Rauch, 1998)).

An approach that can help to meet the future trend mentioned is the implementation of "*flexible small scale production facilities based on standardized modules up to container modules*" (Lang et al., 2012). Compared to conventional plant design, by implementation of modular plants advances in both, efficiency and flexibility are expected to take effect. By application of continuous production processes, recycling streams and heat integration could be included, allowing for a high degree of energy and raw material utilization, automation and a decreased personnel demand compared to batch processes (Buchholz, 2010). Further efficiency may be gained using rather small dimensions of processing equipment, offering a large field of application for process intensification technology (Bramsiepe et al., 2012). Flexibility can be gained in terms of the opportunity for a more agile reaction to changes in market conditions due to shorter lead times expected (Bramsiepe et al., 2014) and stepwise capacity increase using a numbering up approach (Lier et al., 2015). A capacity increase by multiplying functional processing units can also decrease the investment risk by avoiding scale-up issues (Buchholz, 2010). Additionally, the investment risk can be reduced because an early investment can be used to start production at low volumes, providing extra time to gain market insight. In case of low market performance, the production could be stopped without losing a large investment (Bramsiepe et al., 2012). New

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Abbreviations: CEPCI, Chemical Engineering Plant Cost Index; CMR, Controlling, Measuring, Recording; FCI, Fixed Capital Investment; HVAC, Heating, Ventilation and Air Conditioning; ISBL, Inside Battery Limit; OSBL, Outside Battery Limit; P & ID, Piping and Instrumentation Diagram

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products could be introduced quicker as from lab to production scale a small factor applies and standardized modules and simulation models could be used (Buchholz, 2010). Additionally, modular plants could be used as multi-product processes utilizing flexibility through interchangeable structures and the option to avoid production scheduling and cleaning expense by parallel operation of production units (Seifert et al., 2012).

Several approaches to describe modularization have been published. While Jameson (2007) describes a module as just being a mobile unit, a more detailed description has been developed by Burdorf et al. (2004), Kampczyk et al. (2004) and Schmidt-Traub et al. (1999, 2001). In their definition a module corresponds to a main equipment item including its local pipe installation. A module description that also includes standardization of modules has been developed in several research activities in the recent years. Considerable European research projects are for example CoPIRIDE (Löb, 2013) or F³ factory (Buchholz, 2010); further projects are listed by Lier et al. (2015). In the F³ factory project a three tier modular plant approach is used. A module is described as an ISO container that is mobile and equipped with standardized connectors and houses continuously operated process equipment. The process equipment is designed as sub-modules fitting into the ISO container structure. The modules are supplied with utilities and all necessary services from a fixed, generic backbone facility. A detailed description of this concept can be found in Final Report F³ Factory Project (2016).

However, applying a modular design, requires a decent business case including an investment of a meaningful order. Thus, for quantifying the economical applicability of a modular plant special attention should be paid to the investment costs. There are different key figures for the investment costs. In the following we will consider the fixed capital investment (*FCI*), which includes the cost of material, plant construction and overhead costs, i.e. engineering costs and costs of uncertainties (contingencies), but no working capital. It is expected that the modular design affects the investment costs (Kampczyk et al., 2004). In particular, it is assumed that the material, construction and engineering costs are affected to a different degree (Kampczyk et al., 2004; Ricci-Rossi, 1985).

Compared to conventional plants process equipment gets smaller using containerized modules, which means that according to the economy of scale rule there is an increase in production capacity related costs for modular plants. In particular, this applies for process control and process analytics technology (Woods, 2007). For example, the size of a concentration measurement is nearly independent on the stream that is monitored. It is assumed, that material costs (e.g. equipment, piping material, material for electrical installations etc.) are affected as a consequence of scale down, but not as a result of modularization (Behr et al., 2003). Instead, the installation procedures, auxiliaries and equipment design are affected by modularity (Behr et al., 2003), because it is the aim of modularization to use repetition effects e.g. by standardizing components, installation routines and entire unit operations. This does not only apply for the plant components themselves, but also for the outside battery limit components (short: OSBL). Additionally, preassembly of modules under controlled workshop conditions reduces field work and therewith construction costs (Buchholz, 2010). Also, the repetitive use of once developed modules (usability of existing equipment design) will have an impact on investment costs.

The particular impact of each of the cost reduction factors mentioned above will be specific for the boundary conditions of a given investment situation. For example, the option to use existing structures has to be taken into consideration. Here, the expansion of a modular plant with an existing backbone facility by additional production lines has to be distinguished from an investment at the greenfield where also a new backbone facility needs to be installed.

Moreover, comparing modular and conventional design requires that the same methodological approach is applied and the same database is used for the cost estimate of both approaches. We checked state-of-the-art cost estimation methods for coverage of those different requirements.

2. State-of-the-art

In an investment project the level of detail of equipment descriptions increases with the progress of the project (Sattler and Kasper, 2000). Consequently, the quality and amount of information available and thus, the applicability of different investment cost estimation methods changes during the course of the project.

A simple method for order-of-magnitude estimates is the capacity method (Couper, 2003). This method estimates the fixed capital investment of a new process plant by multiplying the fixed capital investment of previously constructed plants that have similar plant configurations and were built on an equivalent site with the ratio of the capacity of the new facility divided by the capacity of the old, raised to a power. The accuracy indicated for this method is ± 30–50% (Couper, 2003). The accuracy of estimates by this method can be increased by subdividing the process plant into various process units (Couper, 2003). Nonetheless, similarity between existing and new process plants is a prerequisite for this method.

A more versatile, yet very simple method has been proposed by Lang (1948). Here, the purchase costs of the equipment delivered (also referred to as delivered purchased equipment costs) are multiplied by a fixed factor, which depends on the type of plant to be constructed (e.g. 4.74 in the case of a continuous plant processing liquids (Lang, 1948)). The delivered purchased equipment costs can be extracted from tables in many textbooks (e.g. Peters and Timmerhaus (Couper, 2003) or Woods (2007)) as soon as the characteristic key figures for an equipment item are known. Thus, for example, for a simple, unlined continuously operated stirred tank reactor made of stainless steel only the indication of the volume is needed (Woods, 2007). The accuracy indicated for this method is ± 30–50% (Couper, 2003).

Lang's method belongs to the class of factor methods of which more detailed approaches have been proposed by Chilton, Peters and Timmerhaus or Miller (Couper, 2003). Factor methods propose a set of factors applied to a key input parameter, typically – as in case of Lang's method – delivered purchased equipment costs, to take different cost contributions into account (Sattler and Kasper, 2000; Couper, 2003; Baerns et al., 2006). The set of factors applied in such methods has been determined on the basis of a number of investment projects. Such factor methods allow for study estimates providing an accuracy of ± 20–30% (Couper, 2003).

More detailed methods for investment cost estimation are historical in-house databases or definitive cost estimation methods as proposed e.g. by Hirsch and Glazier or Guthrie (Couper, 2003). They work with "module costs", whereby a module is a single equipment item to which a set of surcharge factors is applied to take specific cost contributions into account. By adding up the module costs of all equipment items the cost for the complete plant can be calculated. This type of method allows for preliminary estimates providing an accuracy in the range of ± 20% (Couper, 2003).

Hady et al. (2009) developed a modular approach for investment cost estimation in which he proposed a set of nine estimation methods that are applicable depending on the modular complexity level assumed and the project stage. In his approach the modular complexity level is represented by the limits that are used to define a module. This way the cost estimation can flexibly be based on the process equipment level up to the complete processing plant level. The estimation methods proposed are premised on modified capacity and factor methods. However, in his approach no surcharge factor values are suggested nor are possible cost reductions through modularization proposed but such data is implementable once historical cost data for modules is available. Such historical in-house databases will get available only when modular reference plants have been built. Nevertheless, along