POSITION PAPER

Cost Engineering for Modular Plants

Position paper for the evaluation of different plant setups, construction, and operational concepts

Imprint

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Preface

In 2020, the Expert Community Process, Equipment & Plant Technology, PAAT, within ProcessNet started a strategy process to identify synergies and establish new fruitful connections among its working groups. At that time, the Working Group "Modular Plants" just started its regular operation, while the Working Group “Cost Engineering” had published a new cost index integrating more detailed statistical factors. The idea sparked to combine forces and evaluate mutual benefits by addressing key questions such as: How can flexibility of modular plants be measured economically? Which criteria should be analysed when deciding for a modular approach versus a stick-built approach? How can the flexibility in planning, construction, and operation be integrated in early cost estimation methods? How do soft factors such as relocation possibilities or regular product adjustments influence investment decisions? What is the influence of early market supply on the net present value of a plant?

These and other questions were discussed in a common workshop in 2022 with participants from owners and operators, equipment vendors, and academia. The results were meticulously collected, refined, and carefully enriched by experience from early adopters. New aspects and synergies were identified, prompting new topics to be addressed in further research. The results were presented and discussed during the 2023 annual PAAT meeting and subsequently summarized in this paper. Besides a summary of the status, the paper provides new ideas and concepts, which may trigger new developments to strengthen the chemical industry and beyond pushing toward modern technologies and fabrication methods.

Klaus Ohlig, Chairman of DECHEMA/VDI Specialist SectionPEMT (Process Engineering and Materials Technology, formerly PAAT)

1. Motivation

Nowadays, both the chemical and the process industry are facing increased competition and challenges when introducing products in new and volatile markets. To be successful, a fast reaction on market requirements along with a low investment risk is necessary. In addition, shorter product life cycles and smaller product volumes can be observed. These are a consequence of an increased diversification and specialization of the product portfolio due to more client-oriented products. The upcoming digitalization of business processes is also promoting this aspect.

This leads to an increased interconnection between customers and producers, thus to a reduction in required development and delivery times. A fast adaptation to changing market and product requirements is the consequence. Therefore, flexible and cost competitive development and production technologies are needed that can be quickly implemented. Modularization and standardization concepts are available which can provide solutions and need to be introduced and implemented in process technology. Modularization offers flexibility in terms of capacity, product portfolio and production site, standardization, and re-use of engineering effort, thus offering further potential in terms of time and cost savings.

It is obvious from the different nature of these aspects that the value of modularization is not easy to evaluate and express in a single number for an investment decision making. In addition, depending on the context and motivation for an investment project, different aspects of "modularization" and its underlaying concept can be used. It is therefore the intention of this status paper to

- describe and differentiate between the two main aspects of modularization: "modular construction" and "modular flexible plants" and their underlaying benefits compared to stick-built plants.
- discuss the existing methodologies for the evaluation of the various benefits of modularization, and
- recommend a path forward and outline required research and development fields.

The results of an intense exchange between the DECHEMA working groups "Cost Engineering" and "Modular Plants" are described below.

2. Definitions of different plant setups, construction, and operation concepts

The different plant set-ups, construction and operation methods described in this paper start with the traditional stick-built (SB) approach, where all construction activities are carried out at the plant erection site. Differing from the SB approach concepts have evolved where parts of the construction are shifted to a construction yard. Modules are prefabricated there and then transported and installed at the plant erection site. In the following sections, two modular approaches are compared to the SB approach. The "modular construction" (MC) approach is applied for chemical plants of all sizes, while the "modular flexible" (MF) approach tends to be applied more often to smaller capacity plants and is based on using standardized modules to fulfil typical functions in a process plant.

2.1. WHAT IS "STICK-BUILT"?

Traditionally, most process plants are stick-built (SB) and constructed right at the construction site: The individual steps include civil works, equipment erection, field piping installation and electrical and instrumentation installation works. Even piping pre-fabrication could be done in workshops close to the plant erection site. This requires the setup of a large construction organization and facilities at the construction site. Depending on the surrounding conditions, this can be easier or more complex to implement, e.g. when comparing remote locations with locations within well-developed industrial parks.

2.2. WHAT IS MODULAR CONSTRUCTION?

The main objective of Modular Construction (MC) is to transfer construction work from the construction site of a plant into a yard or workshop. This shift has significant impacts on the construction site, the project schedule, and the project's costs.

MC can be applied to a variety of module sizes: From smaller skids in the size of shipping containers, which can easily be transported by trucks or ships up to complete plants, which are then transported to the construction site as "Mega-Modules" using special transportation methods. The size of modules is usually defined by the most economic transport or handling sizes of the modules.

MC can also be applied to different types or scope of modules: They can contain equipment including required piping and instrumentation, but modular construction can also be applied to modules for pipe-racks or even buildings. In this sense, a packaged unit, would be the simplest case of MC.

2.3 WHAT ARE MODULAR FLEXIBLE PLANTS?

The concept of continuous as well as batch production with Modular Flexible (MF) plants is a promising approach to meet the challenges of the chemical and process industry. In recent research projects the technical and economic potential of MF production plants has been demonstrated. Modularization plays the key role in this concept and has been defined for the chemical process industry by DECHEMA and VDI in the 2016 Whitepaper "Modular Plants – Flexible chemical production by modularization and standardization – status quo and future trends" as „Designing functional building blocks with standardized units, dimensions or interfaces, which can be easily assembled, maintained as well as flexibly arranged and operated". (DECHEMA | VDI, 2016)
However, recent developments have shown that defining fixed dimensions of PEAs (process equipment assemblies) and FEAs (functional equipment assemblies) is not always required and often even not useful. This part of the definition has thus lost importance.

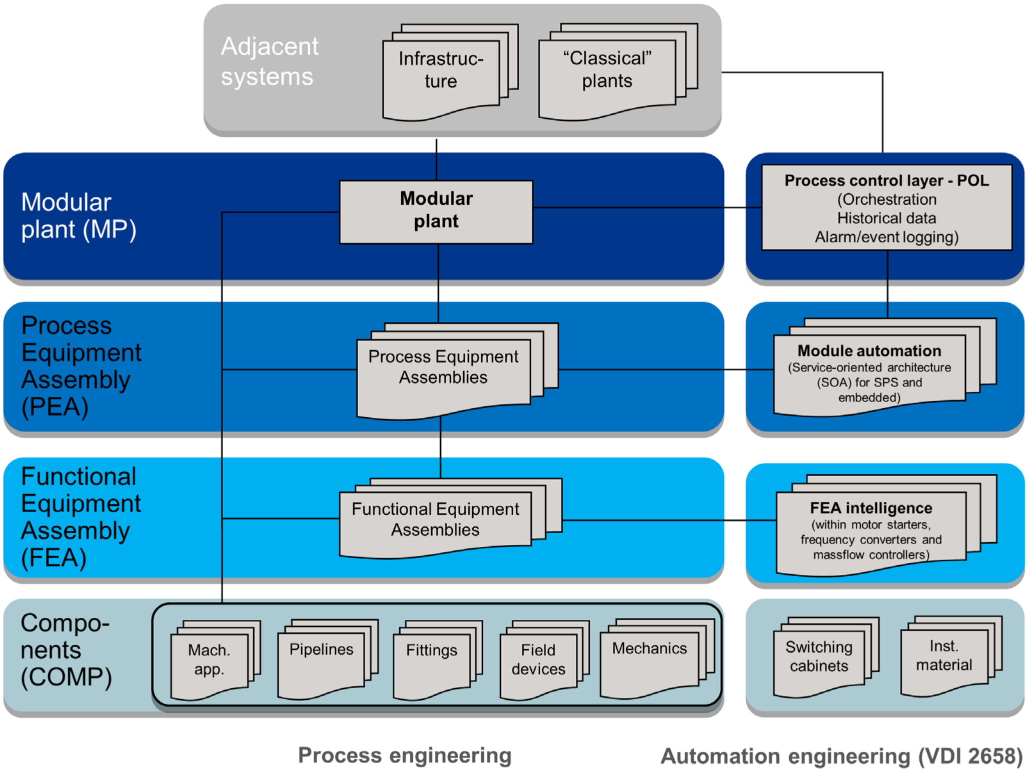

Figure 1: Plant Structure of a modular flexible plant: elements of the modular concept with reference to automation engineering © VDI 2776-01:2020-11

The definition, however, indicates two major differences between a conventional and PEA-based plant design: The first is the focus on a fixed set of process functions to describe process needs on the one hand and PEA capabilities on the other hand. The second is the desire for hardware reuse, which can only be successful when the hardware to be reused is standardized to a certain degree. In PEA-based planning the hardware building blocks to be reused will be developed on the PEA level instead of individual equipment level. The basis for the concept was laid in VDI guidelines 2776 and 2658 describing the elements of the modular plant concept depicted in Figure 1 (VDI, 2020) (VDI, 2022).

3. Overview of criteria for evaluating different construction concepts

The criteria for the evaluation of the different plant set-ups, construction and operation concepts stick-built, modular construction and modular flexible plants are grouped into six different areas: Market, Technical Feasibility, CAPEX, OPEX, Schedule and Risk. A detailed description of the characteristics of the different plant types with respect to the different criteria can be found in the attached Excel file 'Modular and Stick-Built Construction concepts – Scoring.xlsx'). An overview is given in the following chapters.

3.1. MARKET ANALYSIS

A detailed market analysis with its different characteristics is necessary in order to decide which of the described ways of executing plant setups, construction and operation (SB/MC/MF) fits best.

First there is the aspect of the flexibility of the market in terms of product as well as location and volume . What is the lifetime of the product, when are product specifications expected to change? Where do you want to produce, do you expect a change of the production location? Do you expect a stable, fast, or slow or even volatile market growth? SB plants are ideal for products with a long- lasting specification, high volumes, and a stable market in a certain location. Growth rates are expected to be rather small and predictable with a high accuracy. Typically, that is true for commodities.

The same holds true for MC plants in terms of product specification. However, due to the plant characteristics MC plants allow for a certain degree of flexibility for the relocation of plants. In addition, these plants can also be adapted to market volume variations up to a certain degree.

Compared to the plant types mentioned before, MF plants are the most flexible ones. Due to their nature, these plants can more easily be adapted to changing market conditions and are thus suitable for multipurpose / multi-product plants with changing product specifications. These plants usually serve small and volatile growth markets. Even a flexibility in plant relocation can be realized with this type of plant.

Second, there is the aspect for a certain "time-to-market" that the market requires. Is the time-to-realization critical for the business? Is it necessary to be first in the market? The different types of plants offer different options for realization times. Whereas SB plants require the standard duration of an investment project, MC plants offer acceleration opportunities due to parallelization of civil and mechanical construction work. The same holds true for MF plants. On top, this plant type offers further acceleration potential when standard (or pre-engineered) modules are available and can be used.

The third aspect is related to the topic of IP protection. If that is a critical aspect MF and MC type plants offer the best protection because construction takes place in a protected environment.

3.2. TECHNICAL FEASIBILITY

The technical feasibility of the different approaches depends mainly on the individual plant characteristics, but also on the site characteristics. Since for the latter mainly transport and lifting (T/L) issues are important, the plant characteristics can be distinguished between plant capacity, possible copy effects, occupational safety related risks, as well as individual construction requirements.

Starting with the site characteristics, SB plants have low T/L requirements, but high laydown area requirements with possible limitations e.g. in existing industrial parks. T/L requirements of MC plants depend on the module size: heavy haul transportation and good site access together with adequate soil preparation and space for large cranes, etc. usually is required. However, compared to SB plants,a reduced laydown area is required due to less assembling done at the site. MF plants have only low T/L requirements with a minimum laydown area. However, depending on plant layout access to building/infrastructure needs to be considered.

Regarding plant capacity, SB and MC plants can cover all sizes, while MF plants have a typical capacity of approx. 1-30 kt/a. Copy effects are feasible in the early engineering phase for SB, while for MC numbering up is possible in early phases and during detail engineering / procurement as well as parallel execution savings for construction. The highest copy effects are possible for MF plants, depending on the defined process functionalities and site conditions. Concerning the occupational safety during construction phase, SB plants need a larger and more diverse workforce at the construction site, which leads to higher ESH requirements and risks. For MC and MF plants, a smaller and less diverse workforce at the construction site reduces the risks.

Finally, SB plants require large construction and logistic resources at the production site at the same time because the construction site is the later production site. For MC and MF plants, construction resources are split between the construction yard and the later production site. Therefore, it is possible to mitigate site constraints with respect to workforce, etc. in case of limited infrastructure or construction resources on site.

3.3. CAPEX

Figure 2: Construction of a stick-built plant (Source: BASF SE)

CAPEX (Capital expenditures) in the sense of this chapter are the spendings used to engineer and build fixed assets (production plants).

Most chemical plants are engineered and built conventionally, or stick-built (SB) i.e., the vast majority of the plant is constructed at the site where the plant will be operated.
The specific investment costs for this construction method are strongly dependent upon site and country. In general, one can say that for high labor cost countries (e.g., North America, Middle East, etc.) the specific investment costs can be significantly higher than for low-cost countries (e.g. China, India, etc.). The execution approach is normally subdivided into the following steps: engineering process (pre-feed, feed and detail engineering), followed by the construction, pre-commissioning and commissioning phase. The SB execution approach is comparably tolerant to changes in early engineering phases, even though one must keep in mind that the later the changes occur the higher the CAPEX will be for these changes.

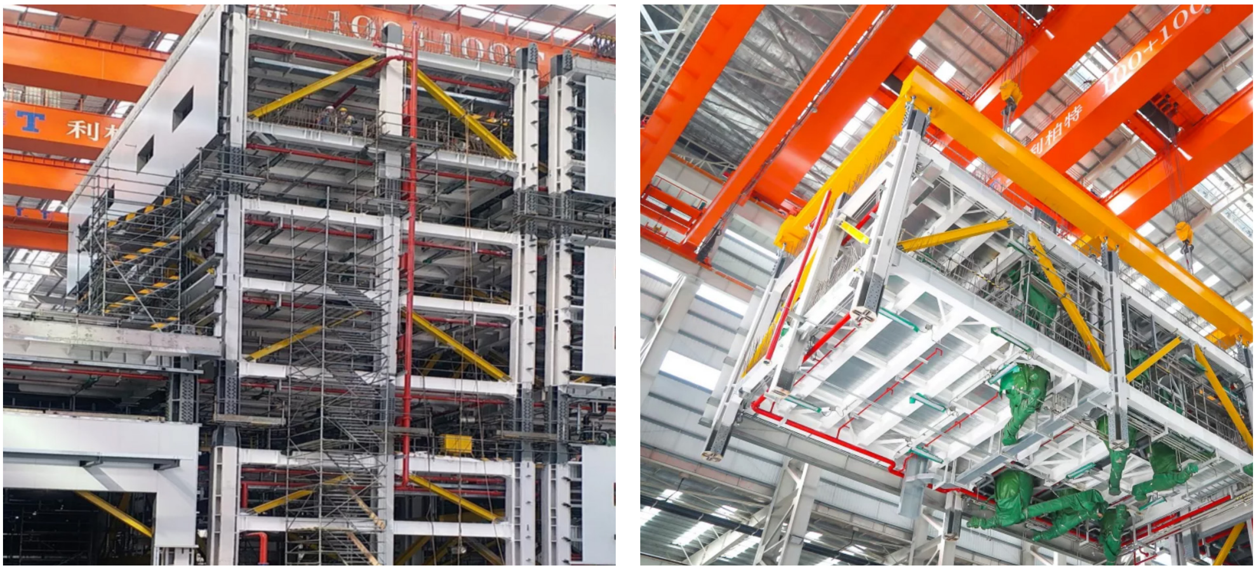

Figure 3: Modular Construction in Yard (Source: BASF SE)

For MC the construction work is shifted to the economically largest possible extent to a module fabrication yard as shown in Figure 3. The module sizes are mainly determined by the conditions of the logistic corridors and can range from one or several bays to whole plants which can be built at the yard and shipped to the site. Main drivers to shift construction from site to a module yard are:

- Challenging and remote environment of the later production site (e.g., deep sea, desert, perma-frost areas, etc.),
- high labor cost on site or
- the mitigation of congestion due to peak construction labor on site.

Depending on the location of the production site costs in the module yard can be more economical due to lower labor costs, higher labor efficiency due to a controlled work environment and well established and optimized pre-fabrication and construction processes. Another advantage is the expected better safety performance at the module yard. On the other hand, MC plants come along with higher weights for structural steel, higher logistic costs, possible import duties, etc. which offsets the advantages to a certain degree.

As a result, for high-cost-countries cost advantages for MC vs. SB are expected. For low-cost-countries other advantages such as schedule, productivity on site, safety, etc. could be the driver to go for a MC approach.

Typically, savings due to economy of scale and 1-to-1 numbering up can be achieved if applicable.

In principle, the engineering process for MC follows the same steps as for SB, however, it is recommended to involve the module fabrication yard early to assure an optimized sizing of the modules. Regarding changes MC is much less tolerant to changes compared to SB.

In contrast to SB, MF plants are characterized by a high degree of standardization of the single modules. This leads to higher initial costs for the development of the design basis as well as automation and safety concepts. Because of the flexible application of the modules (different chemical substances), MF plants come along with higher material requirements and hence higher CAPEX cost for the initial installation.

Thus, the main CAPEX cost advantages of MF plants materialize in the re-use case since most of the engineering work is already done and can be fully re-used. Furthermore, cost savings due to shorter execution times can be leveraged. The “copy effect” for numbering up can be fully utilized for engineering effort and costs for the modules but also on the equipment vendor side and procurement efficiency.

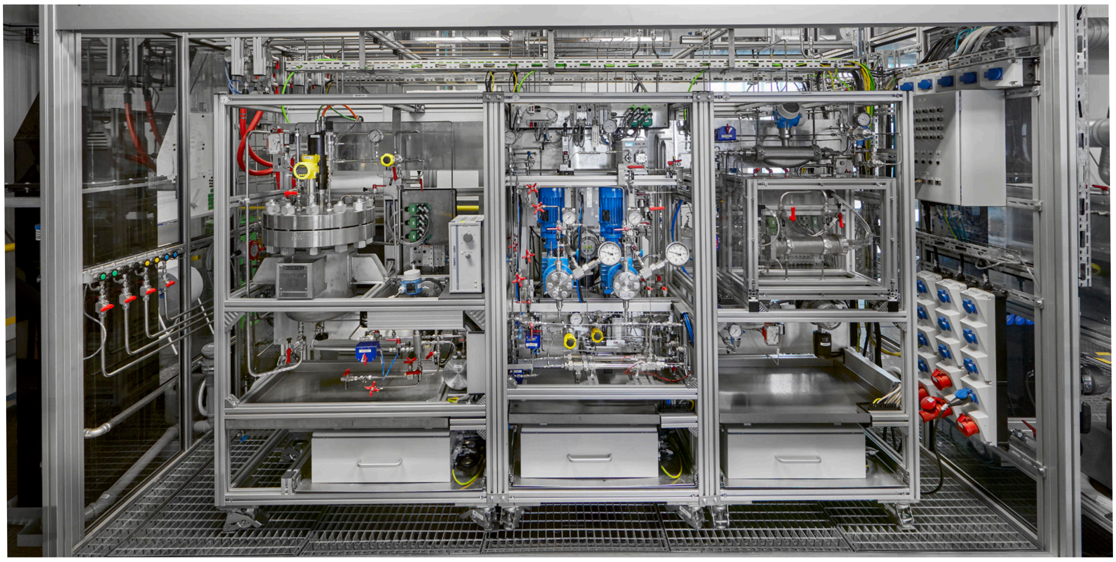

Figure 4: Modular flexible setup (example for a MF plant at miniplant scale Source: Evonik Operations GmbH)

In the engineering process an early involvement of the module specialists is required.

Regarding changes MF plants are highly flexible in the orchestration of pre-defined and standardized modules even at a later stage.

3.4. OPEX

From a perspective of operation, all three execution models entail similar effort for the start-up of a chemical plant, except for applications in a GMP (Good Manufacturing Practices) environment. Here well-(pre) defined modules in MF plants with clear operation procedures can provide significant added value. This leads to less effort in start-up.

In terms of production efficiency and productivity, there are only minor differences between SB and MC regarding potential design restrictions. Design requirements, such as e.g., adjusting volume flows within modules, can be tailored to meet the production's specific needs. Using standard modules from MF plants with already defined design and production parameters might be less efficient e.g., one standard reaction module might be too small, thus a numbering up to two is required. Using optimized modules in the MF approach, which requires some re-engineering, can be as efficient as in the SB and MC approach.

SB plants can be optimized for maintenance requirements. The maintainability of MC and MF modules may be restricted due to limited available space in the modules resulting from more stringent design requirements for transportation purposes. By using and incorporating standard spare modules in the MF approach maintenance by a simple exchange can be very efficient. However, additional space to store the “spare module” is required.

3.5. SCHEDULE

Besides the safety and cost focus, the schedule of construction needs to be considered. Project delays can have a major economic impact for the company.

For MC and MF plants, the construction period can be shortened by the parallel execution of work streams, e.g. site works, civil and module construction can be done in parallel. Module construction can start prior to a completed construction permit which results in a time advantage. In case of a SB approach construction can only be started once the construction permit has been received. All following construction activities are usually executed in a sequential order.

A further time advantage for MC and MF plants is the shortening of the (pre-) commissioning activities. Once the modules are constructed in the yards commissioning activities can be executed (e.g., X-ray, pressure testing, loop checks). Hence no additional commissioning activities need to be done for these modules on site anymore, which is gaining a shorter commissioning phase. For SB approaches these benefits cannot be realized except for the package units where the commissioning could be done in the workshop of the vendor. All other commissioning activities must be done on site.

A last major schedule related decision argument is the flexibility of engineering decisions/design. Engineering departments aim to have as much flexibility during the detail design stage as possible and impose a scope freeze for construction activities as late as possible. This is somewhat contradictory to the modular approach. For MC and MF, the decision what approach to follow should be taken upfront of the engineering process. For MC plants the process & design parameters must be frozen at an early stage which results in less flexibility during the engineering stage. The MF approach offers some degree in design flexibility even at a later stage. Especially the possibility to decide late in the process about the final production site can be of relevance. Advantageous for the SB approach is the fact that process & design parameters can be frozen at a later stage. Even late changes are still possible although they will come with a higher price tag.

3.6. RISKS

Constructing new plants involves a range of risks, such as cost overruns, schedule delays, quality issues, safety concerns, and regulatory compliance issues. The chosen execution method can significantly impact the risks associated with a project.

In the early phase of a project, scope changes are occurring more often than at later stages. Changes usually come with higher costs – the later they need to be implemented, the more costly they tend to be. However, when comparing an SB with a MC or MF approach, changes are still possible. In a MC approach, engineering and procurement must be finished at an earlier stage as compared to SB, which makes the implementation of late changes even more costly. In a MF approach, changes may be a bit easier to be implemented, if a change can be realized by exchanging or adding existing modules.

Regarding a possible change of the plant location, it is obvious that for SB approaches a location change is almost impossible – or comes at extremely high costs. Also, for MC plants risks due to relocation are only slightly smaller. While modules can in theory also be transported to other sites, this will however depend upon the changes in site conditions. On the other hand, MF plants are comparatively easy to relocate to other sites even at a later stage.

Looking at the construction process, the SB approach differs from both modular approaches in terms of its quality risks: SB projects depend upon the availability, fluctuation, and quality of the local workforce. These parameters can be better controlled in the environment of a construction yard for MC and MF projects. Due to the stable work environment, higher automation, and standardization as well as less workforce fluctuation, construction quality is regarded better in MC and MF projects.

As a final point, the SB approach has some advantages when it comes to the risk of interface misalignments. In a SB approach, interface misalignments are usually immediately visible and can be corrected during construction. For MC and MF projects, there may be a certain risk for interface misalignments, and efforts to correct those at the construction site are comparatively high.

All mentioned risks need to be managed during the project and can thus be reduced. E.g., interface misalignments can be avoided by slightly higher planning efforts. Construction quality in SB projects can be managed by contractor selection and quality measures at the construction site.

4. Evaluation methods

In order to decide which execution approach (SB, MC, MF) in an investment project, a suitable evaluation and decision method is needed. Different methods to evaluate the advantages and disadvantages of the various criteria for the three execution approaches are shortly introduced and described in the below. Specific details on the different methods can be found in literature.

4.1. DETERMINISTIC

Static methods of profitability analysis or investment appraisal like cost comparison, break-even analysis, payback period rule, profit comparison or return on investment do not account for the loss in value of money during time. Therefore, these are in most of the cases not suitable to evaluate the different execution concepts introduced above. Conventional chemical production plants traditionally have long life cycles with large investments and decisions at one point in time. In contrast, managers can decide on investments into modules of modular plants sequentially and in shorter time periods. This allows to spread investments over time. Only if the time periods between investments are very short, the time loss effect of money can be neglected. As this is not the case in the evaluation of fundamentally different project execution and production approaches, static methods are not recommendable.

On the contrary, dynamic methods of profitability analysis or investment appraisal consider the loss of value over time. Methods that account for this effect are net present value analysis or dynamic internal rates of return. The net present value analysis is by far the most common and most frequently used method for investment decisions in the chemical industry. Because of this, this method is not described in detail in this paper as it is common and widespread knowledge.

4.2. PROBABILISTIC/ STOCHASTIC

It is clear from the portfolio of economic evaluation methods shown in Figure 5 that the traditional net present value analysis, which is often simplified in practice, does not take the relevant factors of uncertainty and flexibility into account. It should be noted that currently connecting elements of the individual methods are identified and thus, depending on the application, possible shifts in the portfolio may arise. For example, risk-adjusted interest rates can be calculated from the capital asset pricing model (CAPM), or Monte Carlo simulations can be used to determine real-options values.

One way of determining the uncertainty of individual parameters influencing the net present value is to consider different scenarios, e.g., different market developments, or to perform a sensitivity analysis. This method has been used in the past to compare modular and conventional plant concepts, (Lier & Grünewald, 2011). However, a simultaneous consideration of uncertainties of all parameters is not possible with this method. This possibility is offered by simulation methods, e.g., Monte Carlo simulation, in which each influencing parameter can be filled with a probability distribution. The combination of different influencing parameters and simulation runs results in a wide variety of cash flows and thus net present value distributions.

The capital asset pricing model is an equilibrium model from capital market theory that either applies a risk discount to uncertain annual payments or increases the corresponding interest rate with a risk component. In this way, the net present value is determined taking uncertainty into account (Nöll & Wiedemann, 2008). However, the estimates of the risk discount or the risk share are difficult.

The decision tree method also builds on the net present value analysis but distinguishes the points in time between the original investment decision and subsequent decisions at later points in time. Thus, it belongs to a sequential procedure in which decisions are made stepwise. The state-dependent decision sequence that has the maximum expected value of the net present value is sought. However, it might prove difficult to specify all probabilities of occurrence of the different states (Hommel & Lehmann, 2001). Depending on the position in the tree, the risk of the decisions and thus the discount rate changes. An exact adjustment of the risk with the help of a single risk-adjusted interest rate is not possible. All in all, the decision-tree methods provide a conceptual approach to investment valuation, but do not provide an economically meaningful and validated consideration of investment projects with managerial flexibility. Furthermore, its practical manageability is limited (Lier & Grünewald, 2012).

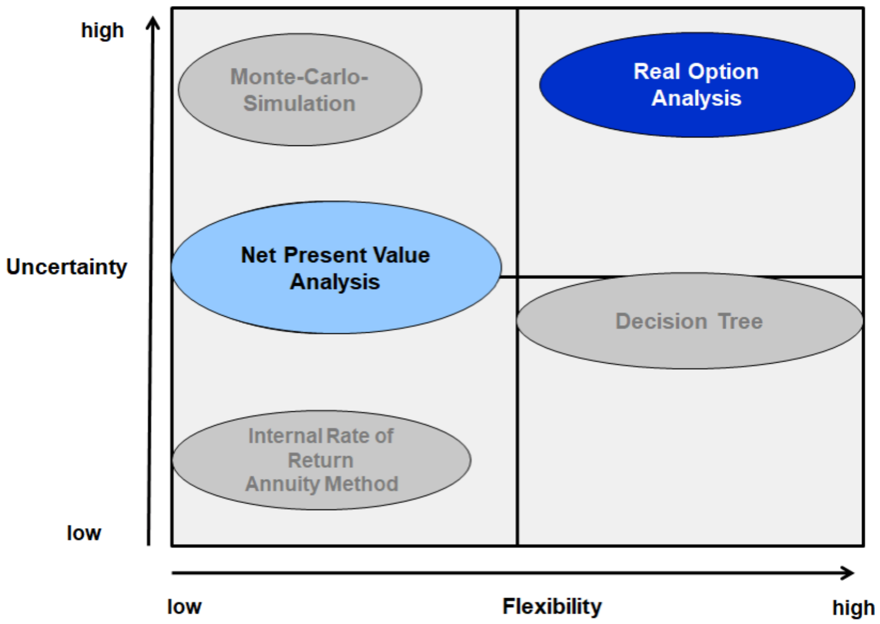

Figure 5: Portfolio of economic evaluation methods based on (Hommel & Lehmann, 2001)

The real options approach has emerged as a potent tool in investment valuation, effectively capturing the inherent value of adaptability and flexibility. This approach is founded on the concept that managerial decisions often share similarities with decisions concerning financial options. Originally, this term was coined to describe investment opportunities as options tied to physical assets, in contrast to financial assets. Just as a financial option grants its holder the right, without any obligation, to buy or sell a financial asset, real options refer to potential managerial actions that are carried out upon favorable circumstances. For instance, managers have the potential to initiate new investments but are not compelled to do so, and they can also choose the timing of their investments. The literature on this topic delves into various types of real options (for overviews see, (Copeland & Antikarov, 2003)), distinguishing between investment options (call options) and disinvestment options (put options). Furthermore, the options-like situation can be related to the timing of an initial investment decision (options to wait or defer) or to potential adjustments to a project following the initial investment. These adjustments may encompass project expansion (option to expand), downsizing (option to contract), project termination (option to abandon), or alterations in the operational mode (option to switch). Modular and flexible plant designs offer multiple options, covering capacity flexibility through expansion and contraction possibilities and providing options to transition between different processes or locations. (Wörsdörfer, Lier & Crasselt, 2017)

Related developments have produced initial real options-based models for assessing the value of modular and flexible plant designs. Case studies employing these models have demonstrated that flexibility holds significant value in many scenarios, particularly when uncertainty prevails. These case studies serve to identify situations in which companies may inadvertently make value-reducing decisions by relying on simplistic methods like the traditional Net Present Value (NPV) approach, instead of more sophisticated techniques such as the real options-based model. (Lier & Grünewald, 2012) (Seifert, Schreider, Sievers, Schembecker & Bramsiepe, 2015) (Wörsdörfer, Lier & Crasselt, 2012)

4.3. SCORING MODELS

Scoring models are useful to derive a decision from criteria which do not measure on the same scale or not quantitatively at all. They consist of the decision alternatives, the weights of the different criteria and points for criterium and alternative. The most prominent representative of scoring models is utility analysis. This method has two main challenges derived from the main criticism of scoring models (subjectivity): the determination of the weights and the calculation of the points. If these weights and points are determined only by the person performing the evaluation and not derived from calculation, objectivity is not given. Therefore, pairwise comparisons of criteria and more sophisticated scoring models like the Analytical Hierarchy Process (AHP) have been developed to solve this challenge and set up calculation rules to derive the weights.

For the points it is advisable to introduce scale transfers (functions between the original scale and the point scale of the scoring model) for a more objective evaluation. Nevertheless, group processes with different experts or independent evaluations of different experts do not only contribute to more objectivity but also help to understand the results with all experts and managers involved in the preparation of the investment decision. Another challenge comes from the interdependencies among the criteria (e.g., time and costs: faster and leaner engineering processes often lead to cost efficiencies). Most of the scoring models assume all criteria are independent. Therefore, the method of Analytical Network Process (ANP) has been developed in which these interdependencies are considered. Scoring models for MF plants have been applied by Wörsdörfer et al. (Wörsdörfer, Lier & Grünewald, 2015), (Wörsdörfer, 2016), (Wörsdörfer, Lier & Grünewald, 2016).

5. Application examples

The following five examples illustrate the characteristics of and differences between the three different construction and project execution approaches and their evaluation. The comparison in the first three examples is performed on the base of the Net Present Value calculation (Pike, 2015).
with an internal rate i=0.15 and a counting period of n=10, the number of years of constant operation and de-

$$NPV = -CF_0 + CF_{xt}\frac{1-(1+i)^{-n}}{i}$$

preciation, too. The annual tax is assumed to be 35%. The net annual cash flow after tax CF_{xt} is the net annual income after tax minus the annual wear cost. The net annual income after tax is the net annual income minus the taxes. The net annual income before tax is annual sales minus the annual production cost. The total plant investment cost, $CF_{install}=CF_0$, is calculated based on the installed main equipment and machines multiplied with a factor from experience for the complete installed plant. This factor depends on the plant complexity and ranges from less than 4 to 6.

Two further examples are illustrated with the real option analysis and the scoring method.

5.1. EXAMPLE A: NPV FOR AN INTERMEDIATE CHEMICALS PLANT (“STICK-BUILT” VS. “MODULAR CONSTRUCTION”)

This case study compares the influence of CAPEX vs. OPEX on the NPV of a SB and MC plant design after 10 years of operation. The example is based on numbers given in (Pike, 2015), based on (Perry, Green & Maloney, 1997) for a fine chemical intermediate production plant with continuous operation. The investigated plant has a capacity of 45 kt/a of a chemical intermediate. The continuous process consists of a surge tank, a preheater, a reactor, heat exchangers, a distillation column, a compressor, a drying column, and a purification column. The total equipment cost of the SB plant is with 9.08 M€, the Total Plant Investment Cost is calculated with a factor 4.5 to equipment cost of 40.84 M€ for the SB plant. The annual production costs are constant for the 10 years with 70.04 M€ with annual wear cost of 0.76 M€. Annual sales are constant, too, with 94.5 M€, meaning a product price of 2.1 €/kg product. The net annual cash flow before tax is calculated to 23.7 M€. Annual tax is calculated to 7.13 M€, leading to an annual net cash flow of 16.57 M€. With these values, the NPV after 10 years of the SB plant is 42.34 M€.

Two different cases of the MC plant are compared with the above values:
1. 10% less investment cost due to better planning and optimized construction, and
2. 10% less operating cost due to cheaper raw materials and energy of the MC plant location.

Figure 6 clearly shows that for lower investment cost, i.e. 90% of the SB plant, the MC plant has an investment of 36.76 M€ leading to an NPV of 45.7 M€ (approx. 8% more). For lower operating cost, i.e. 63.03 M€ per year, the NPV of the MC plant is 65.19 M€ (approx. 54% more). It becomes clear that the main leverage in chemical production would be the lower cost of raw material, personnel, or energy/utilities, leading to lower OPEX. This can be tested individually in the attached Excel calculation sheet ‘Costing-ApparateModuleExampleA-B-C.xlsx’.

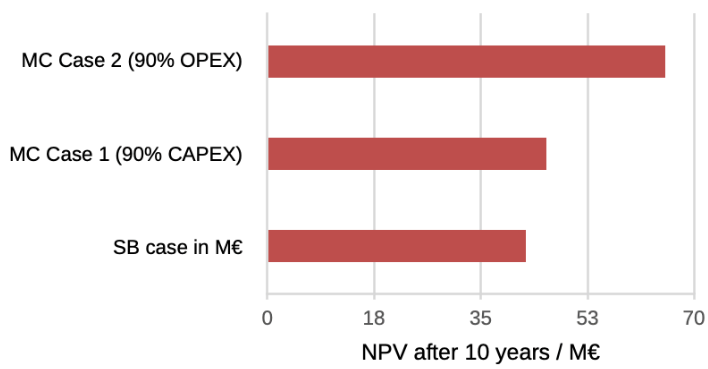

Figure 6: NPV after 10 years for after changing OPEX and CAPEX

5.2. EXAMPLE B: NPV FOR AN AIR SEPARATION UNIT (INFLUENCE OF OPEX/CAPEX COSTS)

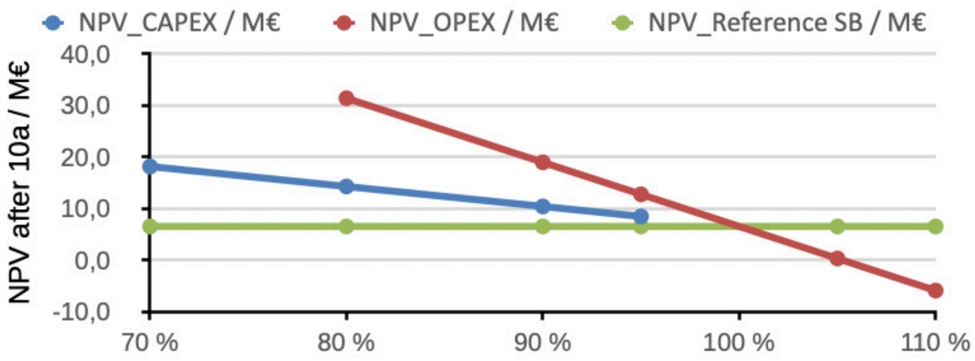

Figure 7: Variation from SB for CAPEX (blue) or OPEX (orange)

This case study compares the NPV of large capacity air separation units in SB and MC plant design with O2 as lead product and with nitrogen and argon as side products. The mainly physical process can either be tailor-made for a single application (in case of SB) or designed with modular components (in case of MC) such as compressor, columns with insulation, tanks, adsorption unit, cooling unit, and buildings. For this case study, the total equipment costs are estimated with 11.75 M€ for SB plant design and with a factor of 4 for the total investment cost of the complete plant, i.e., 47 M€. The total investment cost for a MC plant design is flexibly calculated (5, 10, 20, 30% less in CAPEX) due to better preplanning and prefabrication in combination with a learning curve for the equipment fabrication. In OPEX the SB plant has an annual effort of 38.09 M€, mainly coming from costs for electricity, personnel, and miscellaneous. The product mixture has a complete annual sale of 53.2 M€. For NPV calculation, the operating cost for the MC plant can vary from higher (+10, +5 more) and lower (10, 20% less) values in OPEX due to non-optimal operation in the given module frame as well as lower maintenance cost and/or easier sharing of best practice.

The Net Present Value calculation with 10 years of depreciation, 35% tax, 15% actual rate of return and 0.8 M€ annual wear costs gives 6.53 M€ for the SB plant as a reference value. The NPVs for the different MC configurations are shown in Figure 7. respectively, while the corresponding calculations are provided in the attached Excel sheet 'CostingApparateModuleExampleA-B-C.xlsx'.

The steeper decline of the orange curve shows the larger influence of the OPEX on the resulting NPV, e.g., 10% savings in OPEX have a similar NPV after 10 years than 30% savings in CAPEX. Lower CAPEX of the MC plant leads to higher NPV after 10 years. Higher OPEX of 10% leads to a negative NPV; a value of 5% leads to a nearly zero NPV after 10 years. These effects can be tested individually in the linked Excel calculation sheet 'CostingApparateModuleExampleA-B-C.xlsx'.

For air separation plants, the unit operations are often similar with air compression and purification, main heat exchanger and coldbox with the cryogenic parts as well as product storage and compressor stations. Although the plants were built for a particular location and customer profile, some devices have good potential for reusing equipment for novel plants. The relocation of larger equipment such as the coldbox or the compressor is possible and was successfully shown in the past, too. Furthermore, old equipment was on some occasions used for a "second life", such as with a revamp of rotating equipment (compressors and liquefying circuit), or modernization of cooling circuit, adsorption air drying, or control equipment. This case of a reuse is considered in the scoring method, see example E in chapter 5.5.

5.3 EXAMPLE C: NPV FOR A FINE CHEMICALS PLANT ("TIME-TO-MARKET" VS. "CAPEX")

In the following an example of a fine chemicals production process with 5 kt/a was chosen in order to compare all three different plant concepts. Fine chemicals are typically produced in batch processes with campaigns. Here, the total investment costs for the SB and MC execution approach are calculated from a scale-down of similar known plants to 10.93 M€ and 11.48 M€, respectively. A typical MF plant is scaled up to 5 kt/a resulting in a CAPEX of 12.07 M€ (Pollak, 2012). The production costs of 6.25 M€ are similar for all three types as well as the annual wear cost of 0.20 M€. The annual sales are 10.5 M€ and lead to a net annual cash flow before tax of 4.05 M€ for all three plant designs.

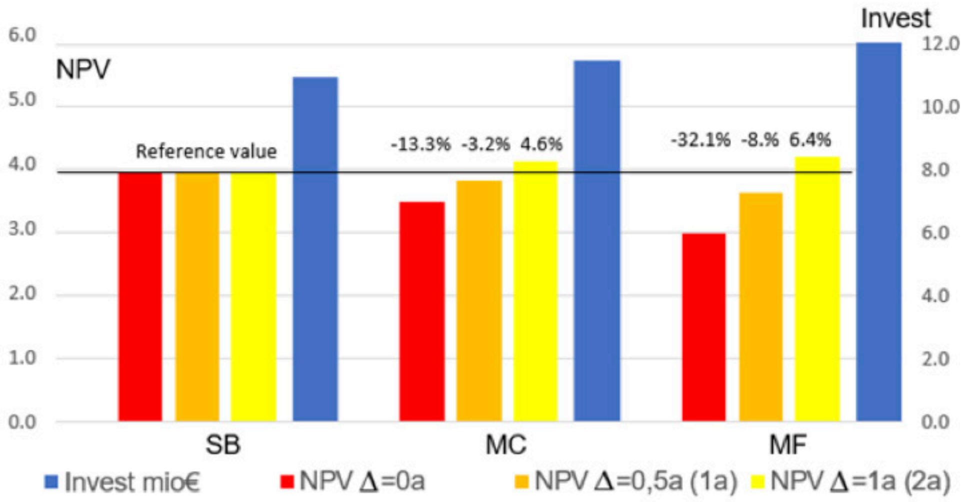

Figure 8: Comparison of investment cost and NPV of the three different plant concepts with three different cases for "time-to-market" scenario

The reference case for the following comparison is the NPV of the SB plant after 10 years in operation leading to a value of 3.85 M€. When the MC and MF plant have the same operation period of 10 years, their NPV is 3.4 M€ and 2.91 M€, respectively. The values are reasonably lower due to higher CAPEX and depreciation cost, see red bars in Figure 8. Assuming a faster implementation time (time-to-market) of the MC and MF plant by 0.5 and 1 year respectively, thus increasing the effective production time, the difference in NPV gets smaller with 3.73 and 3.55 M€, respectively, see orange bars in Figure 8. Finally, when shortening the "time-to-market" for MC and MF plant by 1 and 2 years, respectively, the NPV is higher for both plants than the SB plant with 4.6 and 6.4%, respectively.

5.4 EXAMPLE D: REAL OPTION ANALYSIS FOR INTERMEDIATE CHEMICAL PLANTS ("STICK-BUILT" VS. "MODULAR FLEXIBLE")

Example D compares a SB plant with a MF plant in a real option analysis. The capacity of the stick-built plant (100 kt/a) is divided into four modules of the modular flexible plant with each module having one fourth of the capacity (25 kt/a) of the stick-built plant. The investment costs are estimated at 150 Mio € for the SB plant and 65 Mio € for each of the MF modules. The contribution margin per unit is 1000 € /t for the SB and MF plant respectively and the risk-free interest rate lies at 5 % p.a.. More details can be obtained from (Wörsdörfer, Lier & Grünewald, 2016). Please note that the scale of this example is relatively large for a MF plant, but revenues and costs could be scaled down accordingly. Nevertheless, the example still shows the general approach in comparing these types of plants with the real option method.

The real option analysis calculates an additional value for the flexibility of a MF plant that can handle a certain degree of uncertainty. Details for calculation can be found in (Wörsdörfer, Lier & Grünewald, 2016). Figure 9 shows the (extended) net present value (ENPV) over the uncertainty level of the investment project. Uncertainty is derived from uncertainties of market developments (demand and prices) as well as uncertainties in costs (CAPEX and OPEX). For example, a market development with a forecasted demand for a certain period (10.000t/a in five years for a certain product) can be 20% more in the demanded product amount (12.000t/a) or 20% less (8.000t/year). Usually uncertainties multiply (e.g. market uncertainties and cost uncertainties, which are both part of the NPV) multiply as risk. Summing up the net present value (black) with the added flexibility value (grey) of the MF plant leads to the extended net present value. The traditional net present value calculation would most probably lead to a decision for a SB approach for any uncertainty level in this example due to the higher (classical) NPV value. In contrast to this, the real option approach shows a higher ENPV value for the MF approach for uncertainties of 15% and higher. In conclusion the real option analysis offers an opportunity to calculate a value for certain options of flexibility that can handle a degree of uncertainty.

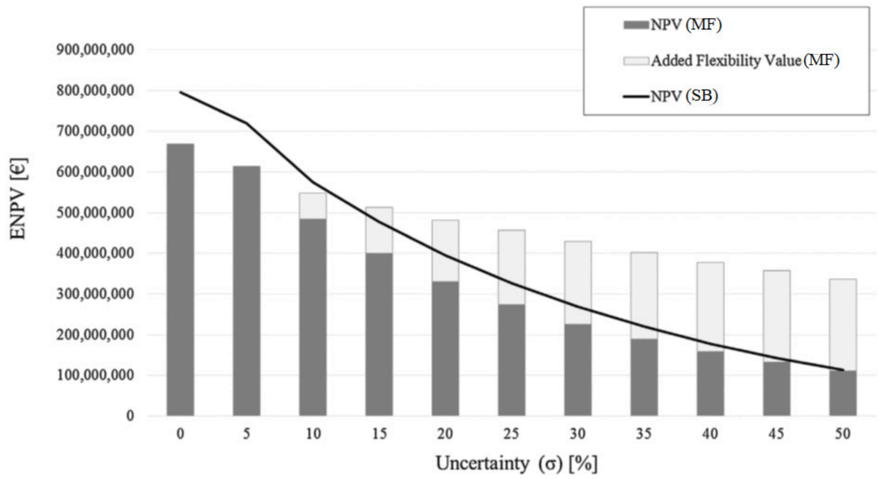

Figure 9: Real option analysis stick-built (SB) vs. modular flexible (MF), based on (Wörsdörfer, Lier & Grünewald, 2016)

5.5 EXAMPLE E: SCORING METHOD FOR AN INTERMEDIATE CHEMICALS PLANT

This example illustrates the use of a scoring method and the impact of parameters on the outcome. The scoring model allows for an inclusion of qualitative criteria if the outcome is not quantifiable in cost advantages for a certain decision. The general procedure for applying a scoring method is outlined in Chapter 4.3.
In the following two scenarios are being applied, both are based upon the fine chemical process as described in Chapter 5.1. Table 1 shows the assumptions for both scenarios.

Criterion	Scenario 1	Scenario 2
Location	United States	Current plan: Germany, with possible later relocation to United States
Schedule	Schedule driven project	Schedule driven project
Portfolio	Stable portfolio	Future portfolio change possible
Expandability	High growth expectations	Volatile market
Capacity	30 kt/a	5 kt/a
Construction site space	Confined construction area	Sufficient space on site
Accessibility	Well accessible	Well accessible

Table 1: Assumptions for two scenarios as base for the scoring method

The application of the scoring method involves mainly three steps:

1. As a first step, the six areas market, plant characteristics, CAPEX, OPEX, Schedule and Risks are weighted (according to their importance) by distributing 100% among the six areas.
2. As a second step, the individual criteria described in the sub-categories are weighted (according to their importance), again by distributing 100% among all sub-criteria of one area.
3. Finally, each sub-category (which has a weight >0%) is rated with a score from 1 to 5. The scores are derived from linear transformation in all quantitative aspects like costs on a scale from 1 to 5. Experts from the industry assess the qualitative criteria independently, their scores are averaged and discussed in an expert group discussion.

Multiplying weights and scores and adding up the weighted scores leads to a sum for each decision alternative (SB, MC, MF).

For instance, the criteria 'Flexibility of relocation' has been weighted with '0%' in scenario 1, because a future relocation is assumed to be out of the question. In scenario 2, it has been weighted with '20%', because the strategy includes a possible later relocation from Germany to the United States.
Another example: 'Capacity' has been weighted with '22%' in scenario 1 and with '11%' in scenario 2. The reason is that in scenario 1 there is a much stronger market growth anticipated. The scores for the three evaluated construction methods range from '1' (MF) to '5' (MC): The ratio behind this is that a plant with 30 kt/a capacity reaches a size, which becomes less attractive for MF modules. On the other side, plants of this size can be well constructed in the SB or MC mode.

The sum of all weighted scores leads to the results shown in Figure 10. Interpreting Figure 10, the recommendation would then be for scenario 1 to go for an execution with a MC plant, while a MF plant would be the second-best solution. It is important to note that the criteria of the desired plant capacity (30kt in scenario 1) may be beyond typical module sizes used for a MF plant. Thus, a MF plant is not assumed to be a viable option in this specific case, especially since there is more growth expected.
For scenario 2, the recommendation would be to go for a MF plant (84%). These scores can be an additional way to include qualitative criteria in the rating and thus are helpful to support the decision-making process.

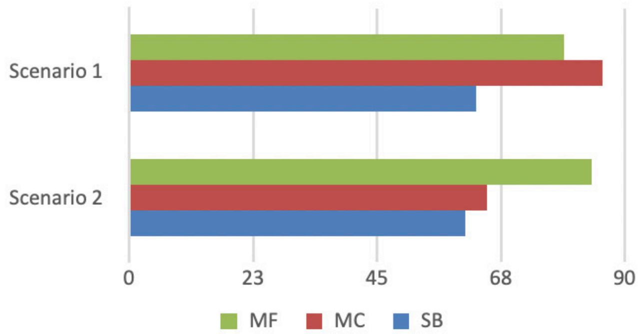

Figure 10: Results of scoring method for both scenarios

The complete example with all weights and scores is available in the attached Excel-table 'Modular and Stick-Built Construction concepts – Scoring.xlsm'.

6. Summary and Outlook

Within this paper three different ways for executing plant set-ups, construction and operation have been introduced and discussed: stick-built (SB) plants, modular constructed (MC) plants, and modular flexible (MF) plants. Besides general aspects and the preferred fields of applications for these concepts the paper focuses on economic as well as qualitative evaluation methods that can reflect the different aspects of the concepts.
In summary the following statements can be made:

· Choosing a certain execution and plant operation concept strongly depends on the respective value drivers and limitations of the underlying investment project.
· All concepts offer solutions to various aspects and criteria that an investment project should address in the long as well as in the short-term view.
· In principle there is no concept superior to the other, nonetheless it is important to decide about the concept as early as possible.
· For a good evaluation of the different criteria for the execution concepts various evaluation methods should be considered to get the full picture.
· Besides established methods (such as net present value analysis) scoring and real option methods offer the opportunity to include more soft criteria (such as flexibility) in the evaluation.
· The evaluation of different aspects of plant flexibility (capacity, process, location) requires additional effort and a re-thinking in the investment decisions.

Within the real option analysis further efforts are necessary to assess product / process and location flexibility from a scientific point of view. A further research gap lies in the combination of different kinds of flexibility (volume, product / process and location). From a practitioner point of view, application tools concerning real option approaches for modularization have to be developed. In spite of the rather complex mechanism in real option analysis of building multiple interconnected trees in various dimensions and implementing the roll back procedure, decision makers in companies need an easy-to-use tool. This must contain the most important input parameters for the different plant concepts and lead to comparable and comprehensible results. Plant manufacturers and operators need to be trained and should test the method in multiple use-cases. The same applies for the scoring model based on the matrix suggested in this paper.

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Glossary

CAPEX:	Capital Expenditures
ENPV	Extended Net Present value
GMP:	Good Manufacturing Practices
MC:	Modular Construction
MF:	Modular flexible
NPV:	Net Present Value
OPEX:	Operational Expenditures
SB:	Stick-built
T/L:	Transport and Lifting

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Attachments

Two Excel-files are attached to this position paper:

- 'Modular and Stick-Built Construction concepts – Scoring.xlsx': This file includes the complete decision matrix with criteria, the tables used for example D as well as a template for applying the Scoring Method.
- CostingApparateModuleExampleA-B-C.xlsx': This file includes the NPV calculations used in Examples A, B and C.

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