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Framework to decide for an expansion strategy of a small scale continuously operated modular multi-product plant

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ABSTRACT

Continuously operated multi-product plants enable an efficient and flexible production of new products. As a future plant concept, a modular design allows the possibility of a stepwise capacity expansion when market demand is increasing. Choosing the right plant capacity combined with a suitable expansion strategy is a key challenge in this context. Therefore, additional costs for expansion have to be balanced against an achievable economic performance and a reduction of investment risk.

In this work a framework to evaluate the production capacity of a continuously operated modular multi-product production line for a production line wise capacity expansion will be presented. As a result, a decision tree analysis integrating production planning by a capacitated lot sizing method is introduced to evaluate the economic performance of plants with different capacities in an uncertain market. The framework is applied for a case study considering a continuous production of a set of three different products. As a key result it can be said that the investment risk can be reduced by applying smaller scale modular production lines. However, the low scalability of investment costs of a small scale production line negatively affects an economic expansion strategy.

1. Introduction

Globalized markets of pharmaceuticals, specialty and fine chemicals are increasingly diversifying. Moreover, global competition leads to increasing market uncertainty and shortened product life cycle of new products [1]. Thus, production flexibility is a key prerequisite for the production of new products.

A fast product launch requires a production of small amounts during market entry. Conventionally, these amounts are produced batch-wise in a multi-product plant that is flexible regarding production rates and products produced [2]. However, batch-wise processing is inefficient in terms of resource consumption [3]. With increasing product amounts a more efficient plant concept is required [3]. Continuous processing offers the possibility of increased production efficiency. Therefore, current research deals with the transformation of batch to continuous processes in small scale continuously operated plants as a future production concept [4]. Different technologies for a continuous processing in fine and pharmaceutical production are investigated [5,6]. Also the Food and Drug Administration urges manufacturers to switch from batch to continuous production [7,8].

For realization of a small scale continuously operated plant, a stepwise capacity expansion seems to be desirable to lower the investment risk in uncertain markets [4]. Utilizing smaller scale production lines allows for time-shifted reaction to changing market conditions by adapting an expansion strategy. Therefore, small scale production lines are required for market entry of new products. Such modular plants which have been recently investigated in funding projects (e.g. F^3 Factory [9], CoPIRIDE [10] and ENPRO [11]) are seen as a desired future plant concept. The strategy of a modular plant concept provides a design by selecting modules instead of designing individually [12,13]. The unit operations of a modular production line are built up by modules which consist of the main equipment and the required peripheral components and instrumentation like piping and process control [4,14]. After product launch, a modular design approach provides the opportunity of fast capacity expansion by numbering-up of the designed modular production line and

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Nomenclature

Cap	Capacity (kg/year)
DPC	Direct plant costs (Mio. €)
EENPV	Expansion included ENPV (Mio. €)
ENPV	Expected net present value (Mio. €)
FCI	Fixed capital investment (Mio. €)
FOB	Free on board costs (Mio. €)
NPV	Net present value (Mio. €)
K	Number of products
M	Number of production lines
NPVaR	NPV at risk (Mio. €)
ROE	Reuse of engineering (%)
T	Time horizon (period)
TCI	Total capital investment (Mio. €)
VaR	Value at risk (Mio. €)
h_k	Inventory holding costs (€/kg)
k	Product k
m	Production line m
n	Degression exponent
p_i	Probability (%)
$p_{k,t}$	Production costs (€/kg)
ppy	Periods per year (periods/year)
pr_i	Production rate (kg/period)
$q^m_{k,t}$	Lot size (kg)
r	Discount rate (%)
s_k	Setup costs (€)
t	Time (period)
$y_{k,t}$	Inventory level (kg)
$\gamma^m_{k,t}$	Product changeover integer

reusing already performed engineering work. This ability to adapt the production capacity to the market development focusing a long-term expansion strategy is known as the expansion flexibility [15,16]. Thus, a modular production line is considered as once designed production line which is copied in case of an expansion.

Investigations on modular design approaches providing the opportunity for this production line wise capacity expansion for single product production have already been published in technical literature. Oldenburg et al. and Wiesner et al. developed a method to evaluate a stepwise plant expansion to a defined market development [17,18]. Their idea of copying a complete production line complies with the modular design concept. Moreover, Lier et al. investigated the expansion of modular production lines regarding an uncertain market demand from an economic point of view [19,20]. They concluded that the investment risk is reduced by a sequential expansion of the production capacity. However, the investment in smaller production capacity and an expansion strategy limits the effect of economy of scale [4].

The production of multiple products within one production line enables a product launch with small product amounts at high plant utilization. Moreover, the investment in a larger scale production capacity improves the economy of scale effect. However, the sequential production of multiple products results in additional costs for inventory and product changeover. When the market demand exceeds production capacity a numbering-up of the production line enables a simultaneous production of multiple products. The design of a smaller scale modular multi-product production line may allow for a stepwise increase of the production capacity. Thus, a simultaneous production on multiple modular production lines is enabled reducing costs for product changeovers of a sequential production when market demand increases.

The decision for a plant concept is conventionally made at early stages of plant design when future markets for the new products are uncertain [21]. An early decision on the plant concept of a continuously operated modular multi-product production line must be enabled. Therefore, a method to decide for a production capacity of a continuously operated modular multi product production line in volatile markets is required when such a plant concept is realized in industry. Furthermore, the option of a sequential expansion needs to be considered. Production planning regarding a multi-product operation must be taken into account. The production capacity available, the costs for inventory and product changeover and a possible loss of sales due to missing opportunities in growing markets need to be determined.

The challenge of determining an optimal expansion strategy for a multi-product plant has been addressed in several publications. The group of Grossmann and Sahinidis developed several methods for a long-range capacity expansion planning [22–24]. Oh and Karimi developed a mixed integer non-linear programming model considering multi-period planning for capacity expansion [25]. However, those methods do not consider the costs for inventory and product changeover. The costs of keeping inventory are generally significant for supply chain evaluation of multi-product facilities [26]. Therefore, production planning in terms of lot sizing multiple products considering inventory and product changeover costs has to be taken into account. Moreover, the expansion strategies considered were optimized applying discounted cash flow (DCF) method calculating the net present value (NPV) as objective function [25]. Regarding a certain time horizon the DCF method determines the NPV calculating the sum of discounted future cash flows [27]. The discounted cash flow is the discounted future value of costs and benefits over a certain period. Assuming a predefined market and a single decision-making event the benefit of expansion flexibility cannot be evaluated by use of the NPV [28,29]. Thus, extended methods integrating market uncertainty and evaluating the option of expansion are required going beyond pure NPV calculations.

In order to consider the managerial option to decide for a time-shifted sequential expansion, two evaluation approaches are recommended [30]. Real-option analysis (ROA) and decision tree analysis (DTA) are integrating decisions on investment and operations including market uncertainty. DTA maps out all possible alternative decisions on all possible events of uncertainty in a hierarchical manner [29]. Mapping out all possible decision and events at discrete points, the DTA enables to compute unconditional expected cash flows by taking account of conditional probabilities of each event [29].

The outcome of the DTA is therefore contingent on the path of the decision tree. Thus, the major drawback of DTA is the difficulty to specify all conditional probabilities of different events inside the tree. Depending on decisions and events the risk changes in the tree which leads to the problem of determining the appropriate discount rate as the main shortcoming of DTA [29]. ROA overcomes this shortcoming by applying financial option pricing techniques. Instead of generating discrete events in a tree at certain probabilities, all possible events are considered by adjusting probability distributions within a risk neutral validation [29]. Thus, the consideration of probability distribution of future cash-flow paths can provide a better result than DTA.

Schwartz and Trigeorgis have shown that methods to evaluate investment options by DTA and ROA are operationally identical [29]. In general, ROA is theoretically superior and more accurate when generating a correct value of a project including the available flexibility [30]. In certain cases, when risk is diversifiable and the outcome of a project is just dependent on a technological risk, ROA