A Model for Cost-Benefit Analysis of Production Ramp-up Strategies

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Abstract. Production ramp-up is a critical step in product life cycle as it could lead to either success or failure of product introduction into the market. The criticality of this step is owed to several factors including the uncertainty underlying this step regarding both expected costs and benefits, and thus to the complexity of decision-making. In order to enlighten decision makers particularly in multi-variant production contexts, this paper elaborates on an analytical model supporting cost-benefit analysis of production ramp-up strategies. The model takes into account capacity planning decisions and learning curves in determining cost-benefit estimates. The model is illustrated and discussed through a keyrings manufacturing process.

Keywords: Ramp-up, Cost-Benefit, Costing, Analytical Model, Variety.

1 Introduction

Manufacturing and service industries are challenged more than ever by market volatility and shortened product life cycles. As a result, frequent production and service introduction into the market and increasingly varied offerings has become key features of nowadays industry. However, successfully introducing products into markets is not an easy task particularly in high variety production [1] [2]. More specifically, the shift from prototype development to stable production is a critical phase entailing high uncertainty and lack of relevant information to take proper decisions [3][4]. This is heightened by high offering variety aiming to offer customers a wider spectrum of choice [5]. High variety production ramp-up is a critical step in product life cycle as it could lead to either success or failure of product introduction into the market [2][6]. The criticality of this step is owed to several factors including the challenging costing and cost-benefit analysis tasks of unstable production [7]. Accordingly, this paper addresses the following questions: *What are the challenges of ramp-up management particularly with regards to cost modelling and cost-benefit estimate? Do existing ramp-up models cover the cost perspective of multi-variant production ramp-up? And, how to adapt traditional models to production ramp-up*? To address these questions, the remainder of the paper is organized as follows: Section 2 reviews ramp-up challenges and identifies the main gaps in the literature. Section 3 derives a model supporting cost-benefit analysis of ramp-up management strategies. The model results from a joint research effort of researchers and practitioners. Section 4 illustrates the model using a simple use case. The paper ends with discussion and concluding remarks in Section 5.

2 Ramp-up management overview and challenges

In their effort to consistently deliver customized products and services, companies are faced with a continuous multi-product development and ramp-up [1]. While ramp-up is very determinant phase in product life cycle, it received less attention than both design and stable production phases in particular considering high variety production environments [2][6][7]. While there are several definitions of ramp-up, it is commonly accepted that ramp-up is the connecting phase between product development and series production [8]. Ramp-up phase plays a major role in successful new and innovative products introduction into the market. Production ramp-up is however challenged by increasing product variety resulting in high operations complexity [4][9] (see Figure 1). This challenge is partly owed to evolving customer requirements and new interoperability issues underlying Industry 4.0 concept [8] [10]. As such, the complexity spans over both product and processes, thus adding to the criticality of decisions on production volume. This figure is prevailing in multi-variant and small-lot size production [11]. Therefore, adequate approaches and operational frameworks are needed to holistically address ramp-up management of multi-variant production. Depending on product and process complexities, different ramp-up strategies can be distinguished focusing on achieving volume production of standard products (i.e. high-volume-low-mix) or ramping up the production of a set of products variants at low volumes (i.e. low-volume-high-mix) [2].

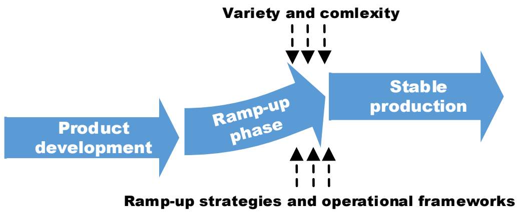

Fig. 1. Ramp-up management in product life cycle

As a matter of fact, ramp-up management decisions particularly impact on and are impacted by capacity planning, learning effects and operations cost , which have in turn mutual influences [7][12][13]. Capacity is usually limited at the beginning of and during the ramp-up phase, which requires increasing it incrementally in particular in high complexity production [13]. Such increase involves however investment decisions which should be supported by a cost-benefit analysis. Furthermore, there is high uncertainty underlying operations before reaching production steady state which decreases progressively with the increase of experience-based learning acquired by the personnel [14]. Both of these factors greatly impact on operations' cost during the ramp-up phase. In this sense, authors such as [7][12] highlighted the lack of attention to holistically addressing several ramp-up management perspectives such as cost, capacity and learning.

Ball et al.[7] proposed an analytical model to fill such gap, through modelling the impact of changes within the ramp-up phase. The model was however not explicitly described. Furthermore, product-mix and variety in general are not considered. Most of cost models which apply to ramp-up consider learning and learning curves [10]. Arguably, learning is progressively improved during ramp-up therefore cost effectiveness is also improved. Subsequently, it could be reasonably inferred that speeding up the ramp-up phase is at stake for manufacturing and service companies as a means to reduce costs and to ensure a timely introduction into the market [4][9]. In this sense, learning can be introduced as a factor in cost modelling during ramp-up and different scenarios can be distinguished in order to enlighten decision makers. The idea of holistically addressing ramp-up was partly addressed in a more recent study from [13]. While the proposed planning model is relatively comprehensive, it was focused upon operational performance with no explicit representation of the cost dimension.

Costing during the ramp-up phase is only partially dealt with, firstly because of the lack of holistic frameworks allowing to consider the joint effect of different factors. In this sense, more tailored costing models are needed, which can be derived from the most common approaches such as bottom-up, analogous, and parametric costing [15]. In fact, while sound models have been developed consistently with these basic approaches, most of them do not consider the ramp-up learning and capacity effects. In a nutshell, an adequate costing model should reflect learning effects, capacity and production features. Further on, to effectively support informed decisions on a given alternative ramp-up strategy both investment and operations costs (outflow) and operations income (inflow) should be holistically depicted and analyzed. In this sense existing cost models should be complemented with inflow models. Next section elaborates a model for addressing these issues in the context of ramp-up management.

3 Cost-benefit analysis of ramp-up management strategies

This section elaborates on a model aimed at enabling support decision-making on ramp-up management strategies in discrete manufacturing. It applies to the life cycle phase starting right after finishing realizing product development. Indices and sets, and indicators for assessing ramp-up strategies are detailed in the following.

H	set of time-box periods covering the ramp-up phase
$\mathcal{A} = \{a_1, \dots, a_A\}$	set of products included in company's portfolio
d_a^t	demand volume of article a at period t
v_a	selling price of product a
$\mathcal{M} = \{m_1, \dots, m_M\}$	set of potential equipment to be invested in
c_m	purchasing cost of equipment m
l_m^t	maintenance cost of equipment m at period t
k_m^t	maximum capacity of equipment m at period t
δ_m	binary variable such that $\delta_m = 0$ if m is automated

$L_m: H \longrightarrow [0,1]$	learning function, such that $L_m^t = L_m(t)$ is the learning level about equipment m at period t. The closer is $L_m(t)$ to 1 the higher is the learning effectiveness.
T_m^x	wage (per period) of operating equipment m
$\mathcal{B}$	set of raw material and components
q_b^a	bill of material coefficient referring to quantity of raw material or component b required to produce one unit of product $a \in \mathcal{A}$
n_a^t	production volume of product a during period t
s_m	salvage value of equipment m
T_m	useful life time of equipment m
f_b	unit cost function of raw material or component $b \in \mathcal{B}$
$\phi(m, a, t)$	binary function such that $\phi(m, a, t) = 1$ if equipment m is used to produced product a at period t

The learning process is assumed to follow a specific function which generally increases with experience. It is assumed that equipment is used continuously and extensively thus limiting forgetting risk, subsequently forgetting effects are not considered. Furthermore, it is assumed that demand is known for the periods belonging to the ramp-up phase, automated equipment does not require human resources. The model suggests to evaluate a given ramp-up strategy through a cost-benefit computing function. To this end, sales turnover (benefit) is calculated based on demand volumes and on planned production volumes. Besides, variable and fixed costs are calculated (cost) based on planned production volumes and on the chosen investment strategy in capacity and considering learning function. Following a straight-line depreciation, depreciation D can be written as follows, we assume that $\forall m, T_m \geq H$:

$$D = \sum_{m \in \mathcal{M}} \sum_{t \in H} \frac{c_m - s_m}{T_m} \times \max_{t_0 \leq t} \left(\left\lceil \frac{\sum_{a \in \mathcal{A}} n_a^{t_0} \phi(m, a, t_0)}{k_m^{t_0} L_m^{t_0}} \right\rceil \right) \quad (1)$$

Assuming that demand of given period is satisfied exclusively by the production of the same period, operations cost can be calculated as follows:

$$C = \sum_{t \in H} \sum_{m \in \mathcal{M}} (l_m^t + T_m^x \delta_m) \left\lceil \frac{\sum_{a \in \mathcal{A}} n_a^t \phi(m, a, t)}{k_m^t L_m^t} \right\rceil + \sum_{t \in H} \sum_{a \in \mathcal{A}} \sum_{b \in \mathcal{B}} n_a^t \, q_b^a \, f_b(n_a^t q_b^a) \quad (2)$$

Sales turnover can be written as follows, such that $n_a^t \leq d_a^t$:

$$S = \sum_{t \in H} \sum_{a \in \mathcal{A}} v_a \times n_a^t \quad (3)$$

Since the main objective of the model is to enlighten decision maker through cost-benefit analysis of a given strategy, decision variables involve selected equipment m (capacity and number) as well as planned production volumes n_a^t. These variables depend on a variety of factors which are not exhaustively addressed by the model. In fact, the scope of the current model is limited to show the impact of a given ramp-up strategy rather than providing an optimal solution. In fact, current model is intended for supporting a cost-benefit analysis through integrating both investment and operations' costs (cost) and sales (inflow). This scope is quite consistent with the commonly used

Profitability Index (PI) which is derived from the Net Present Value (NPV) concepts. NPV supports the evaluation and comparison of several alternative investment options. PI represents the rate of present value of cash inflow to required investments. In the current model, PI can be written as follows:

$$PI = \frac{S}{D+C} \tag{4}$$

4 Illustrative use case – keyrings manufacturing

The illustrative use case involves a small SME providing accessories and concerned with ramp-up the production of keyrings $\mathcal{A} = \{a_1, a_2, a_3, a_4, a_5\}$. The horizon of the ramp-up amounts to 24 months. For each of the articles $a \in \mathcal{A}$, two profiles are considered for the demand d_a (Figure 2). A seasonality is introduced in demand forecast of three of the five articles in the second profile (D2). Selling prices v_a are as follows 10 €, 10 €, 14 €, 8 € and 12 €, respectively.

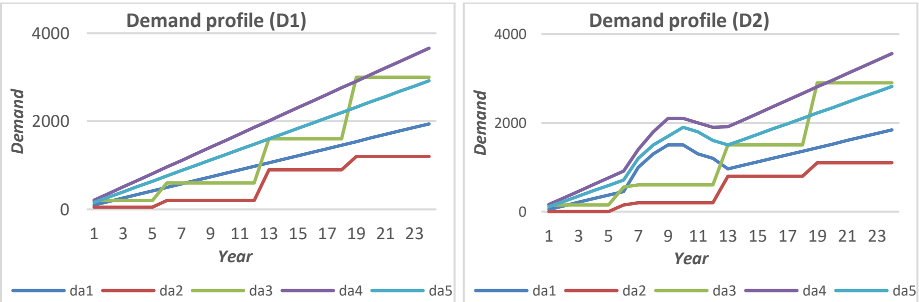

Fig 2. Demand profiles throughout ramp-up phase

All five products have one-level bill of material, raw materials unit costs and consumptions are shown in Table 1.

Table 1. Material consumption

Material	Designation	Cost function	Quantities a_1	a_2	a_3	a_4	a_5
w_1	Grey paste	$f_1(q) = 8$	0,01	0,01	0,01		
w_2	Purple paste	$f_2(q) = 8$	0,01		0,01		
w_3	Blue paste	$f_3(q) = 10$	0,01	0,01			
w_4	Plastic	$f_4(q) = 7$				0,012	0,012
w_5	Ring	$f_5(q) = 0,5$	1	1			
w_6	Ring-luxury	$f_6(q) = 1,5$			1	1	1
w_7	Water	$f_7(q) = 0,01$	0,001	0,001	0,001		

In order to meet market demand, the company needs to plan its capacity based on a set of available equipment. Characteristics of the possible equipment to produce the keyrings are detailed in Table 2. For each equipment (Equip.) we assume salvage value (s_m) represents 20% of purchasing cost (c_m) and $T_m = 36$ months. Two learning functions are considered as shown in Figure 3. Monthly operator wage is $T_x = 2000$€.

Table 2. Equipment characteristics

Equip.	Operation	Products	Purchasing cost	Maintenance cost	Maximum capacity
m_1	Preparation	a_1, a_2, a_3	5 000 €	50 €/month	9 600 unit/month
m_2	Cutting	a_1, a_2, a_3	7 500 €	100 €/month	3 200 unit/month
m_3	Cutting	a_4, a_5	10 000 €	100 €/month	4 800 unit/month
m_4	Assembly	$\forall a \in \mathcal{A}$	7 500 €	200 €/month	3 200 unit/month
m_5	Decoration	$\forall a \in \mathcal{A}$	10 000 €	200 €/month	1 600 unit/month
m_6	Cooking	a_1, a_2, a_3	12 500 €	100 €/month	3 200 unit/month
m_7	Finishing	$\forall a \in \mathcal{A}$	5 000 €	50 €/month	3 200 unit/month

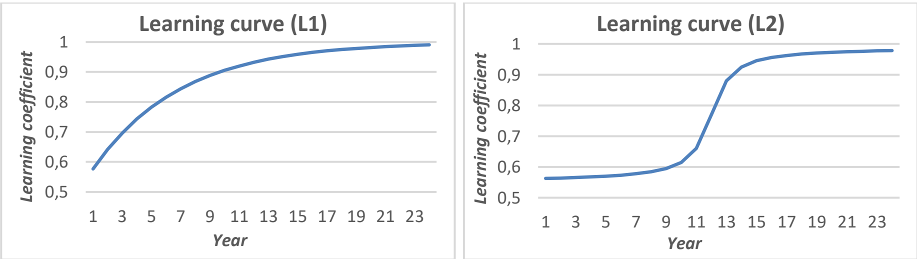

Fig. 3. Learning curves

In order to illustrate the model, a parallel ramp-up policy was adopted which consists of simultaneously ramping-up the production of all products. The ramp-up process is ruled by a capacity matches-demand planning strategy, aiming to align equipment investments with demand forecast. In total, four scenarios were evaluated considering two demand profiles and two learning curves. The model was implemented in Excel for illustration purposes. Results were double checked for consistency. A summary of the scenarios, main model inputs, demand profile, learning function (in addition to above data) and outputs, *PI* are provided in Table 3.

Table 3. Ramp-up strategies evaluation results

Scenarios	Demand profile	Learning function	*PI*
D1-L1	D_1	L_1	1.55
D1-L2	D_1	L_2	1.37
D2-L1	D_2	L_1	1.50
D2-L2	D_2	L_2	1.40

It can be seen from Table 3 that Profitability Index is sensible to both the learning and demand profile. However the impact of learning curves was higher with almost 10% variation in *PI* value compared to less than 1% variation induced by introducing seasonality in demand profile. As shown in Figure 4, all four scenarios uncover an initial period with total costs exceeding sales profit. This period, ranging from 3 to 6 months, is higher when the learning process follows the second learning curve (L2) (top right hand side in Figure 4). The impact of seasonality is reflected basically in the new trends of sales and cost curves (bottom graphics in Figure 4). Both demand and learning can be assumed to be exogenous variables to the decision making process on production ramp-up. The case study shows however how these variables can impact the ramp-up phase from a cost-benefit perspective.

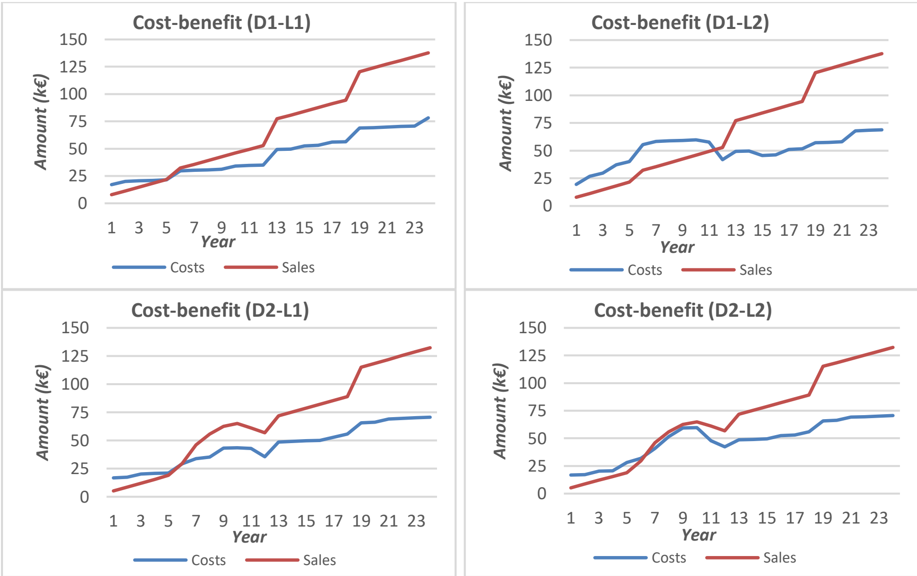

Fig. 4. Cost-benefit results

5 Discussion and concluding remarks

Increasingly evolving business environment and technological advances uncovered promising opportunities to reinforce customer-oriented operations. Conversely, this poses new challenges to both manufacturing and service sectors, which is to frequently develop and introduce new customized products. This adds to the complexity of ramp-up management as scaling up high-mix production is much more challenging than low-mix production.

The current model supports the decision making process during production ramp-up while considering both product mix and ramp-up phase peculiarities, i.e. learning and capacity planning decisions. The model relies on cost-benefit analysis to evaluate ramp-up strategies. While there is a well-established body of literature on cost modelling and estimation, it is argued that peculiarities of ramp-up phase requires both adaptation of these approaches and enrichment to integrate the benefit perspective. Through integrating a bottom up cost modelling and profitability assessment, current model complements existing literature by integrating cost modelling and benefit assessment of ramp-up strategies. Furthermore, the model contributes to addressing the lack of operational frameworks for ramp-up management through its ease of use and relatively limited amount of required data.

In a nutshell, the paper sheds more light on the economic perspective of ramp-up phase while integrating factors such learning and demand profile. While the case study was selected for illustration purposes, it uncovered very promising research opportunities that are being explored and addressed in ongoing research and projects. This includes the analysis of different ramp-up strategies of multi-variant production in order to build a set of contextualized recommendations to some specific business environments. Furthermore, the model is being improved in order to provide not only a cost-benefit evaluation but also to recommend best set of strategies through optimization. These research perspectives are being explored in collaboration with an industrial partner and within the framework of the two ongoing projects VARIETY and SUSTAIN.

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