A scaling-up methodology for co-rotating twin-screw extruders

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Abstract. Scaling-up of co-rotating twin screw extruders is studied as a multi-objective optimization problem where the aim is to define the geometry/operating conditions of the target extruder that minimize the differences between the values of the performance criteria that depict the reference and target extruders. Three computational experiments are discussed. These preliminary results seem encouraging.

Introduction

Scale-up and scale-down are two important operations in co-rotating twin screw extrusion, as very often one needs to transfer the processing settings from laboratory to production plant units or vice-versa, while maintaining the same product characteristics [1].

Currently, most extruder manufacturers offer a range of machines with different sizes, but having constant external to internal screw diameter ratio (this determines the free volume) and, in some cases, identical specific torque. Although the idea is to guarantee similar shear histories, extruders of different sizes have inherently different surface-to-volume ratios, thus affecting the heat transfer efficiency, with consequences on flow, mixing and viscous dissipation [2]. Thus, geometrical similarity between extruders is not enough for adequate scale-up. Consequently, several authors derived power-type relationships, usually applicable to the fully filled sections of the machine and based on simplified flow analyses, that scale machines of different sizes in terms of similar degree of fill, mean residence time, throughput, mixing quality, melt temperature, etc [2-6]. One obvious difficulty is that scaling for one parameter will provide different results than scaling for another parameter. This means that choices have to be made [2]. The situation becomes more problematic when both the reference and target extruders exist, so that scaling-up consists in defining the screw profile and/or the operating conditions of the latter. Indeed, most existing rules focus on the diameter ratio.

Ideally, a scaling-up method should:

- consider simultaneously the various relevant process parameters and provide information on the degree of satisfaction of each that was achieved by the solution proposed;
- rely on accurate descriptions of flow and heat transfer along the machine;
- take in the various screw geometrical parameters and operating variables.

The authors attempted to apply such an approach to the scaling up of single screw extruders [7]. They regarded scaling-up as a multi-objective optimization problem where the aim is to define the geometry/operating conditions of the target extruder that minimize the differences between the values of the performance criteria that depict the reference and target extruders. Similar strategies were adopted to design single and co-rotating twin screws [8,9].

The present work aims at applying the same principles to the more complex case of scaling-up or scaling-down co-rotating twin screw extruders.

Scale-up as an Optimization Problem

Optimization methodology. The aim of extrusion scale-up is to guarantee identical thermo-mechanical conditions in both the reference and target extruders. This is done here through solving the optimization problem where the aim is to obtain the operating conditions and/or the geometry of the target extruder that minimizes the differences in performance between both extruders [7]. The corresponding procedure involves five sequential steps: i) compute flow and heat transfer in the reference extruder (using an appropriate modelling routine) for a specific geometry and operating condition; ii) define the process parameters that should be considered for scale-up; iii) select the geometrical and operational parameters of the target extruder to be defined, as well as their range of variation; iv) perform the optimization; v) select the best solutions proposed.

Two basic routines are needed, one for process modelling, another for multi-objective optimization [10,11]. The latter is based on a Multi-Objective Evolutionary Algorithm (MOEA) developed previously by the authors [12].

Modelling. The modelling routine used considers the entire path of the material from hopper to die [13]. The following individual steps are modelled: 1) solids conveying without pressure, 2) solids conveying under pressure, 3) melting; 4) melt conveying under pressure and 5) melt conveying without pressure. Their sequence depends on the screw profile and operating conditions.

Computations are performed from the screw entrance to the die exit. The first restrictive element is identified. Then, an iterative procedure spots the location upstream where the channel becomes fully filled. The calculations proceed along small channel increments. In the first restrictive element solids conveying, melting and melt conveying are included, while in the remaining only melt conveying is assumed. The program computes the evolution along the screw of pressure, average and maximum temperature, shear rate, viscosity, mechanical power consumption, degree of fill, deformation, residence time and specific mechanical energy. More details can be found elsewhere [13].

Scale-up objectives. The objectives to be selected must consider the predicting capabilities of the modelling routine. They can assume two shapes: a value, reflecting the global extruder response (e.g., maximum or average melt temperature at die exit, average residence time, average deformation, specific mechanical energy), or a function describing the evolution along the screw of, for example, melt temperature, pressure, shear rate, viscosity, or degree of fill. These objectives are incorporated in the methodology via the following equations:

$$F_j = \frac{\left|C_j - C_j^r\right|}{C_j^r} \qquad (1)$$

$$F_j = \frac{\sum_{k=1}^{K} \frac{\left|C_{j,k} - C_{j,k}^r\right|}{C_{j,k}^r}}{K} \qquad (2)$$

where F_j is the fitness of criterion j, C_j and C_j^r are the values of criterion j (single values) for the target and reference extruders, respectively, and $C_{j,k}$ and $C_{j,k}^r$ are the values of criterion j on location k (along the extruder) for the target and reference extruders, respectively. The aim is to minimize F_j, which varies in the range [0;1].

Optimization runs

A Clextral 21.25 twin screw extruder was used as reference (see screw configuration in Table 1), while a Leistritz LSM 30.34 was selected as target extruder (Table 2 presents the geometries of the 16 elements available). A polypropylene (ISPLEN PP030 G1E, from Repsol, see properties in [13]) is being processed in the Clextral machine with a flat barrel temperature of 220ºC, a feed rate of 8 kg/hr and a screw speed of 200 rpm.

Table 1. Screw profile for the reference extruder (Clextral 21.25). KD-45 denotes a block of kneading discs with a staggering angle of -45º.

Screw Element	1	2	3	4	5	6	7	8
Length (mm)	250	50	50	50	50	50	50	50
Pitch (mm)	33.3	25	16.6	KB -45	33.3	25	16.6	KB -45
Screw Element	**9**	**10**	**11**	**12**	**13**	**14**		
Length (mm)	50	50	50	50	50	50		
Pitch (mm)	33.3	25	16.6	KB -45	25	16.6		

Three different optimization (scale-up) runs are reported here:

- assuming that the 16 elements of the target extruder produce a meaningful profile, define the operating conditions;
- for the reference and target extruders operating under identical conditions, define the best sequence of the screw elements of the latter (elements 1 and 2 will be kept in their initial positions);
- as in the previous run, fix the operating conditions and define the screw profile, but now allow also the staggering angle of the two kneading blocks to be also optimized. More specifically, the angles can take the following values: 90º, 60º, 45º, 30º, -30º, -45º, -60º.

In all cases, three objectives were included: i) average melt to barrel temperature ratio - a measure of viscous dissipation (T/Tb), ii) average strain and iii) specific mechanical energy (SME).

Table 2. Screw elements of the target extruder (Leistritz LSM 30.34).

Screw Element	1	2	3	4	5	6	7	8
Length (mm)	97.5	120	45	60	30	30	30	60
Pitch (mm)	45	30	KD -45	30	-20	60	30	20
Screw Element	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Length (mm)	37.5	120	30	120	30	60	60	30
Pitch (mm)	KD -60	30	30	60	20	45	30	20

Results and Discussion

Figures 1 to 3 present the Pareto frontiers for the 3 runs. The Pareto frontier is a surface representing the trade-off between the three objectives, shown here as two 2D plots.

As seen in Figure 1, it is easy to minimize the T/Tb objective, as the differences between the two extruders are always lower than 10%. Conversely, the differences for the other two objectives main reach 40%.

When comparing runs 2 and 3 (figures 2 and 3), it becomes evident that varying the geometry of the kneading blocks brings on more flexibility to the optimization, since the range of variation of the objectives becomes much higher.
The best screw configurations minimizing each of the objectives in run 3 are presented in Tables 3 to 5. The corresponding objective function values are gathered in Table 6.
The screw minimizing the T/Tb objective is similar to that of the reference extruder, with the restrictive elements distributed along the axis. The average strain objective is minimized for a screw with a longer kneading block (the two restrictive elements are adjacent to each other), but at the cost of large differences in SME. Finally, the SME objective is minimized when the kneading blocks have positive staggering.

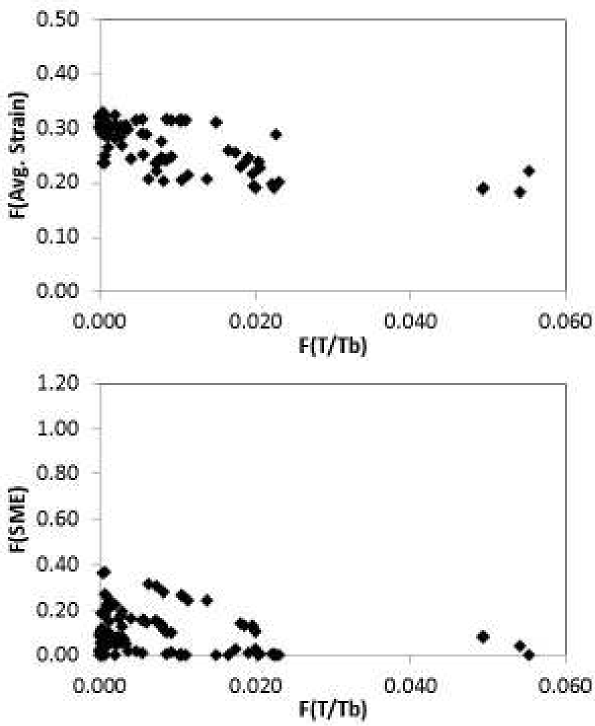

Fig. 1. Pareto frontiers for run 1.

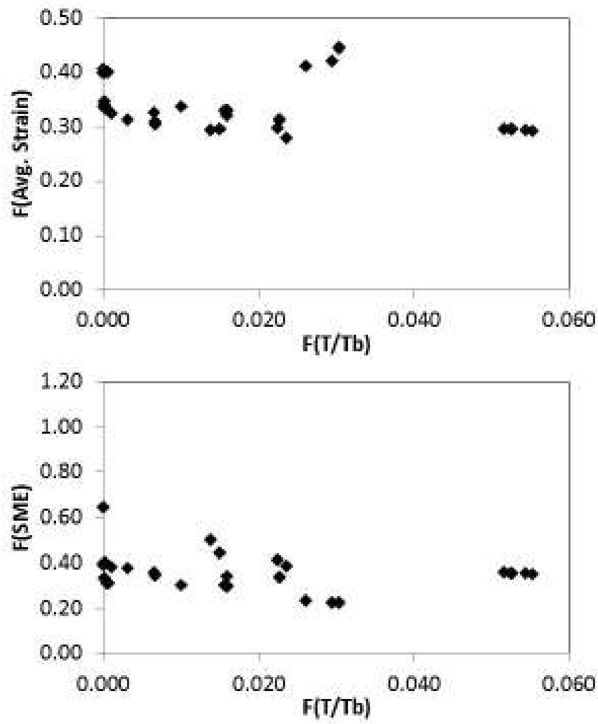

Fig. 2. Pareto frontiers for run 2.

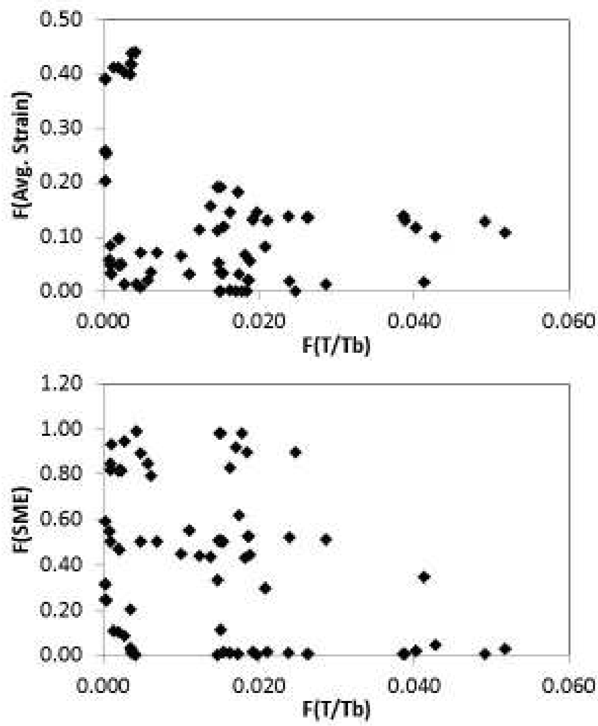

Fig. 3. Pareto frontiers for run 3.

Table 3. Screw configuration minimizing T/Tb (run 3 – Screw 1).

Screw Element	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Length (mm)	97.5	120	30	60	60	60	120	60
Pitch (mm)	45	30	-20	20	30	30	60	45
Screw Element	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Length (mm)	30	45	30	30	30	120	30	37.5
Pitch (mm)	20	KD -60	60	30	30	30	20	KD -30

Table 4. Screw configuration minimizing the average strain (run 3 – Screw 2).

Screw Element	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Length (mm)	97.5	120	30	45	37.5	30	60	120
Pitch (mm)	45	30	20	KD -45	KD -45	30	30	60
Screw Element	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Length (mm)	30	30	120	30	30	60	60	60
Pitch (mm)	60	20	30	-20	30	20	45	30

Table 5. Screw configuration minimizing SME (run 3 – Screw 3).

Screw Element	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Length (mm)	97.5	120	30	30	30	30	60	60
Pitch (mm)	45	30	60	30	30	20	20	30
Screw Element	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Length (mm)	30	120	60	30	45	37.5	120	60
Pitch (mm)	-20	60	30	20	KD 45	KD 90	30	45

Table 6. Objective function values for run 3.

Screw	*F(T/Tb)*	*F(AvgSt)*	*F(SME)*
1	*0.0002*	0.3909	0.3160
2	0.0185	*0.0002*	0.8971
3	0.0041	0.4397	*0.0002*

Conclusions

Scaling-up or scaling-down of co-rotating twin screw extruders is approached as a multi-objective optimization problem, instead of using correlations covering individual process performance parameters. Three computational experiments illustrate the potential of the method. Further developments are required to convert the method into a useful tool for practical application.

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