Process simplification asks for a yardstick, quantification of plant complexity

J.L.A.Koolen
Retiree Dow Chemical Terneuzen The Netherlands
E-mail jla.koolen@wxs.nl

Abstract Process simplification and process intensification are trends in the process industry to lower capital investment and improve performance of operation. The trend to build smaller and simpler find broad appreciation in industry and research. Simplicity of design or in reverse term complexity of design currently does not have a bases for comparison. In this article a complexity factor on bases of units and plants has been developed. The complexity factor is composed of the following contributing terms; equipment, DOFs for operation, measurements, streams involved, level of interactions and level of disturbances. The contributing terms are adjusted with a weight factor for items like identical and similar units and levels of interaction The complexity factor has been applied for different units and process sections from small till large industrial units and clearly showed the difference in complexity. Reduction of the contributing terms like by installing less equipment and full automation clearly show a decrease in complexity of a design.

Introduction

Process simplification and intensification are a strong upcoming trend in process design. They both have as objective to reduce the cost of the installation and as such its economic performance In this respect the term process simplification is mostly reserved for application of known technology, process intensification is often used for new developed technology. A simple and robust plant is defined as :

” *An optimal designed safe and reliable plant, operated hands-off at the most economical conditions”*.

Such a plant is designed according to ten design philosophies as developed by Koolen ’01 which are:

1. Minimize equipment, piping and instruments.
2. Design for single reliable and robust components, unless justified economically or safety wise.
3. Optimize design.
4. Clever process integration.
5. Minimize human intervention.
6. Operation optimization makes money.
7. Just-in-time production (JIP), with key elements: avoid or minimize logistic facilities.
8. Total quality control (TQC), with the key elements: prevent versus cure and first-pass prime production.
9. Inherently safer design, with the key elements: Minimize, Substitute, Moderate, Simplify.
10. Environmentally sound design.

Special attention should be paid to minimal human intervention. A simple and robust plant is designed in such a way that the operation is close to full automation (only supervisory actions of operation), while the control system of the plant has a robust disturbance rejection capability by a balanced control strategy and by de-coupling the interaction of control loops by model based controllers. These model based controllers are part of the design and preferable developed based on dynamic simulations to support design and operation as training tool.

The concept was illustrated by comparison of a domestic refrigerator with an industrial refrigerator. This example clearly illustrated the difference between two complete different design approaches, see Table 1. The domestic refrigerator was designed totally hands-off with only the set-point for the temperature as operational degree of freedom (DOF), while it was purposely designed maintenance free. The industrial refrigerator was designed as a complete set of units with all types of measurements, controllers and actuators like valves for operation and maintenance where foreseen in the design.

The question addressed in this paper is; can process simplification be quantified - simplicity is often defined as less complex, therefor the question is rephrased in; how can process complexity be quantified. The need was felt to quantify the complexity of a process to mark the difference between designs and to identify the terms which play a role. The minimization of the contribution terms will lead to simpler designs, and give insight in the impact of these terms.

What is simple?

> *"A system or device is simple if the user understands its purpose and is able to operate it with few manipulations while any wrong or unstructured manipulation does not result in any damage".*

This definition learns why most domestic equipment is simple, its purpose is know and its use is restricted to a limited number of manipulations. Let us mention some domestic examples:

- An electric light has as function to give light and is manipulated by a switch,
- An television set gives a view on the (quasi) living world and is manipulated by an on-off switch, a program selector and a volume adjustment, - all the rest of the manipulators is for installation or nice to have and not required for its basic function
- The engine of a car is the driving device and is manipulated by an ignition switch, accelerator and its operation is observed by speed indication and oil pressure alarm.

The above examples all have a well known purpose and limited number of manipulators while the devices as such may be very complicated to design and like a car engine or a TV-set.

Table 1. Comparison between domestic and industrial refrigerators.

Technical points	Domestic	Industrial	Technical points	Domestic	Industrial
Safety devices	–	17	Equipment	1	10
Instruments to control system	1	58	Filters	–	5
Instruments, local	–	20	Reliability	Very high	To be proven
Control loops	1	9	MTBF in years	>10	1
Valves	–	120	Spare unit	None	One

MTBF = Mean Time Between Failures

Ref: Koolen '98

By listing the components of a domestic refrigerator versus an industrial refrigerator as shown in Table 1 the difference in complexity will be clear. The domestic refrigerator is a unit which is designed as one unit for the user while operation is limited to the adjustment of a set-point. In contradiction the industrial refrigerator is build of a set of equipment components, valves and instrumentation which require a lot of actions from the operator while surprisingly enough the unit has an installed spare unit to cope with any malfunctioning. This last example clearly shows the difference between domestic and industrial units.

Quantification of Complexity

The term 'complexity' is introduced when a total system is considered. It was Scuricini (1988) who defined the complexity of a system as:*"A system is complex when it is built up of a plurality of interacting elements of a variety of kinds, in such a way that in the holistic result no evidence can be traced of the characteristics of single elements".*

The factors which determine complexity are: (Alkemade '92, Scuricini '88, Wieringa and Stassen, '93)

- the number of components;
- the number of interconnections;
- the number and level of interactions; and
- the variety of components.

From an operational perspective can be added;

- the number of measurement readings,
- the DOFs for the operator; and
- the surveyability of the state of the system.

When we consider these from a unit operation perspective in a process plant these terms are translated and accumulated in a complexity term C as follows:

The level of complexity, C, of a unit in a chemical process is defined as a function of:

- M, the number of equipment accessible by the operator;
- N, the number of DOFs, including manual/actuated valves/switches and set points of control loops;
- O, the number of measurement readings;
- P, the number of input and output streams, including energy streams;
- Q, the interaction in the unit requiring operator intervention;
- R, the number of disturbances (for the unit) asking for more corrective actions from an operator

Note: the interaction and disturbances which are absorbed by the system and which do not require any operator intervention are ignored. This is favorable for those systems which have an automation and control system which are designed to cope with these effects.

In formulae form: $C_{\text{unit}} = f\,(M)\,(N)\,(O)\,(P)\,(Q)\,(R)$, (1)

where C is called the complexity factor of the unit. Currently there isn't any measurable concept of complexity and it has to be to approached with hypotheses. The major problem is that complexity depends on human factors which are difficult to measure A hypothese to translate this equation in a usable simple form was e.g. mentioned by Kline '90 and Wieringa '92, the summation of individual terms. To cope with diversity of these terms a weight factor was added for each term, its relative contribution can now be valued.

Complexity becomes now: $C_{\text{unit}} = mM + nN + oO + pP + qQ + rR$, (2)

where m, n, o, p, q, r, are weight factors per term.

In generic terms: $C_{\text{unit}} = \sum_{1}^{n} a_n A_n$ (3)

where a are the weight factors and A the individual terms.

A specific term can be further split up if we want to give different weights within a term. Let us look at the manipulators N: these consist of manual valve W, actuated valves in general connected to control system X, switches (as DOFs) Y, set points Z, the respectively weight factors are in small letters.

$N = wW + xX + yY + zZ$ in generic terms $N = \sum_{1}^{n} b_n B_n$

where b are the weight factors and B the manipulators.

For a process plant, which is a summation of individual units, we can add up the individual unit complexity factors: Complexity of process plant: $C_{\text{plant}} = \sum_{1}^{n} c_n C_n$ units, (4)

Where c_n are the weight factors per unit and C_n units the unit complexity factors.

Complexity of piping is an item which can add considerably to the complexity of a system and is often a source for mishaps, small and very large, potentially resulting in catastrophic events. In particular the surveyability of a process system suffers from complex piping systems.

Complexity of piping based on the same approach is defined as; $C_{\text{pipe}} = f\,(M)\,(N)\,(O)\,(Q)$ (5)

M is number of lines, including bypasses, cross-overs;

N is the number valves, automatic as well as manual including bypass, drain and vent valves;

O is the number of piping items others than valves, such as check valves, reverse and excess flow valves, safety relieve devices, bellows, reducers are excluded these are seen as part of the fixed pipe; and

Q is the number of flow interconnections.

These terms clearly show how the complexity of piping grows by adding terms

Like the complexity factor for units the piping complexity factor can be linearized and summation of the

terms gives the formulae Complexity of piping $C = M + N + O + Q$ (6)
The approach to make piping system less complex can easily be achieved by; avoiding of equipment less equipment reduces the number of lines, minimize valves, minimize piping items, avoid interconnected piping systems to reduce the number of potential flow interconnections.
This last point can be illustrated, a piping system with 6 connections which creates 30 flow interconnections. Replacement of this system by two piping systems with 3 connection the number of flow interconnections reduces to 2 × 6 = 12. The term complexity of piping can be handled as a separate term in the complexity of process plant C plant, equation (4), although the manipulators already included in the complexity factor of unit need to be eliminated.

The value selection of the weighing factors needs an argumentation, see Table 2.
From the viewpoint of operation of a unit, identical or similar units for the same application (like separation by distillation of the same mixture) are easier to handle (less complex) than a different processing step. While a similar unit for another application (like another distillation) is also easier to handle than a different processing step. We can put these in a ranking order with increasing complexity; identical unit, similar unit for the same application, similar unit for an other application, compared to a reference unit. In the same category also fall identical temperature measurements installed in a packed bed in a horizontal plane or spare units like refrigeration units, pumps and compressor sets. The assumption that identical unit only limited contribute to the complexity is generally accepted by operation. The arbitrarily selection of the weight factors for units is based on this argumentation.
The weight factors for control with respect to interaction demanding operator intervention require a different argumentation. It is known that the ease of control as experienced by operators is heavily dependent on the level of interaction between different sub systems. The terms playing a role are: the order of the systems, the gains of the interaction between subsystems positive and negative, the number of subsystems effected, the training and experience of operators, (Stassen et al ‘93, Wei et al ‘98). The perception of operators about the control complexity as experienced is not yet fully known over the range of interest neither are there operational performances. Although there is not any doubt about the trends. Stassen et al 1993 defined a complexity index in relation to a single loop as:

$$\text{Complexity index} = [(1 + k)^{n} - 1]/nk \qquad (7)$$

where k is the interaction gain and n the number of subsystems
The results of their confirmation tests - which were imposed disturbances at a system to be counteracted by control changes of operators to maintain the output of all subsystems at a desired output value - were measured as the operational performance which was taken as a measure for the interaction complexity. The variables were n and k for first order systems where k was positive. The results clearly showed the exponential impact of the number if subsystems n and the interaction gain k on the complexity. Literature does not yet give correlation over the full operating range with all involved parameters to define process complexity to cope with interaction. It was decide to select process conditions to enable the determination of the weight factors for interaction based on the above equation. The factor for a single loop without interaction was 1.0 while the weight factors for an interaction gain of 1 for respectively 3 and 6 subsystems are 2.5 and 10.5.
Disturbances which require operator intervention need to be prevented in a simple and robust process plants which require a minimum of operational support. There are three ways to deal with them: prevention, rejection and absorption which are all three applied, while they might be caused by external as well as internal causes. During control design attention need to be paid to minimize operation intervention at disturbances. Disturbances makes operation more difficult and require attention and performance. As there isn’t any research done in this field there is currently no other solution than arbitrarily selecting a criteria. The number of different corrections/manipulations to be made by the operator to neutralize a disturbance is selected as criteria for a weight factor.

Table 2. Weight factors for different items

Item	Weight factor	Item	Weight factor
Identical unit or spare unit	0.1	Single loops	1.0
Similar unit for the same application	0.2	Interaction with three subsystems	2.5
Similar unit for another application	0.5	Interaction with six subsystems	10.5
Identical measurement in radial position of vessel	0.1	Disturbance requiring 3 corrections	5
Equipment	1	Disturbance requiring multiple corrections	10

Examples Now, we can calculate a complexity number for units based on weight factors of 1, examples for quantification of complexity are;

- For a household refrigerator M = 1, N = 2 on/off switch and temperature set point, O = 0, P = 1 electricity, Q = 0, R = 0. Now the complexity is C = 4
- An industrial refrigerator as presented in Table 1 based on an existing situation, the complexity factor C is build up from the following terms M = 10, N =129 valves and loops, O = 78 instruments, P =3 power cooling water and refrigeration duty, Q = 0, R = 3 refrigeration duty, cooling water and power, the Complexity factor becomes now C = 223
- A car engine M=1, N= 2 ignition switch and accelerator, O = 2 speed indicator and oil pressure, P= 2 gas and air, Q = 0, R = 0. Complexity C = 7
- For a simple TV set M = 1, N = 3 on/off switch, program selector and volume, O = 0, P = 2 electricity and signal cable, R = 0. Now the complexity is C = 5
- For a normal distillation column a P&ID was analyzed. The values of the different terms are: M = 8 (tower, reflux drum, reboiler, condenser, two reflux pumps, two bottom pumps); N = 89 (control valves 7, manual valves 67, DI/DOs 9, control loops 6); O = 28; P = 12 (feed, bottom, distillate, vent stream, steam, condensate, cooling water in and out twice, electricity twice); Q = 2 interaction between compositions, and R = 3 (feed flow, feed composition, cooling water temperature). So, the complexity for the selected distillation column is: C = M + N + O + P + Q + R =142

It can be concluded from these examples that there is a wide spread in complexity factors C of the selected units as calculated through this method. The range goes from 3 for a domestic refrigerator through 143 of a distillation column.

In the above discussion a weight factor was introduced to be used for weighing the different terms leading to a complexity factor.

As example case a comparison is now made between the design of two sequential distillation columns and a divided wall column to separate three streams

The complexity factor for the combination of two sequential distillation columns based on the data as used above but including the weight factors The complexity factor for one column for M = 8, N = 89, O = 28, P = 12, Q = 2.5 ×2, R = 10×3, becomes C = 172

For two sequential columns, the weight factor 0.5 selected for the second column is based on similar but for another application (separation). The complexity factor for the two columns becomes now C = 172 + .5 × 172 = 258

A divided wall column, a three stream splitter, does only marginal differ from a standard column. The differences are an additional side stream with a outlet flow controller (flow measurement, flow valve, set-point), some additional temperature measurement (say 3) in the column and additional 2 interactions caused by the additional outlet stream. This result in an increase of the standard distillation column of 187 with 6 + 10 × 2 =26 resulting in a divide wall column complexity factor of 213. This number is considerable less than for two distillation columns.

Another example case is a reactor followed by a distillation column for separation compared to a reactive distillation for the same system. When the system with the separated functions reaction and distillation is compared with the reactive distillation we observe the following additional equipment and terms. The system has an additional heat exchanger and two recycle pumps M = +3, while studying the P&ID's the number of actuators (DOFs) N = + 48 and measurements O = + 8 are increased and the number of streams is increased with one P = +1, the interaction and disturbances terms are the same Q = 0 and R = 0. Based on these data the unit with the separate up-front reactor but similar terms with respect to disturbances and interaction has a higher complexity factor, C is + 60.

In these last two examples it is assumed that the units have an adequate control design to decouple interaction and provide disturbance prevention and rejection. A detailed dynamic simulation of such a system is a prerequisite to enable such a design and is a inherent part of simple and robust design.

The complexity equation is applied to different units and demonstrates that it useful to discriminate on complexity between different designs. From the formulaes it can be concluded that the complexity of a unit/process can be reduced by minimizing the terms in the complexity equation.

Automation ask specific attention. It was a study of Wei et al '98 who measured system performance by operators, (seen as a measure for operational complexity), as a function of level of automation for a system with 12 first order sub systems. The conclusions were clear, a higher level of automation results in higher system performance, this support the design philosophy of simple and robust plants hands-off operation . The one button operation like for burner management need to achieve wider application.

Discussion

The above illustrates the usefulness of applying a quantitative method to differentiate process units and plants in terms of complexity. The contributing terms to the complexity are encapsulated in the formulae and it will be clear that reduction of these terms leads to less complexity. To be mentioned are; less equipment, less manipulations by operation like valves and controller set-points (DOFs) this asks for a higher level of automation, less superfluous measurements limit it to the essentials, de-coupling of interaction and disturbance prevention and rejection by robust control. To achieve robust control to de-couple interaction and reject all standard disturbances a dynamic simulation might be required to design adequate controllers. The increase of the level of automation can even achieve a one button situation for a refrigeration unit but also reactor systems can be automated.

Literature

Alkemade M.J.A. Inspelen op complexiteit, (inDutch), 1992 Samson, ISBN 90-14-03883-6

Kline S.J. A numerical measure for the complexity of systems: The concept and some implications, Stanford Univ. (CA) report INN-5, 1990

Koolen J.L.A., Design of Simple and Robust Process Plants, Wiley-VCH, 2001, ISBN 3-527-29784-7.

Koolen J.L.A. Simple and Robust Design of Chemical Plants Comp.& Chem.Eng.Vol. 22 s255-262 '98

Scuricini G.B Complexity in large technological systems in Measures of complexity ed. Peliti l, Vulpiani A, Lecture Notes in Physics Vol 314 p 83-101 Spriger-Verlag Berlin 1988 ISBN 3-540-503 16-1

Stassen, H.G., Andriessen, J.H.M., Wieringa, P.A. On the human perception of complex industrial processes. 12th IFAC World Control Congress, 1993, Vol. 6, pp. 275–280.

Wei ZG, Macwan A.P., Wieringa P.A., A quantitative measure for degree of automation and its relation to system performance and mental load, Human factors Vol 40, no 2 1998 pp 277-293

Wieringa, P.A., Stassen, H.G. Assessment of complexity. In: *Verification and Validation of Complex Systems: Human Factors Issues* (Wise, J.A., Hopkin, V.D., Stager, P., Eds.), Springer-Verlag, Berlin, 1993, pp. 173–180. ISBN 3-540 56574-4.