Chapter 2

Self-consistent inventory control

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Inventory or material balance control is an important part of process control. A requirement is that the inventory control is *consistent* meaning that the mass balances (total, component and phase) for the individual units and the overall plant are satisfied. In addition, *self-consistency* is usually required, meaning that the steady-state balances are maintained with the local inventory loops only. To state the importance of consistency, if a control structure is inconsistent, then at least one control valve will become fully open (or in rare cases closed) and cannot attain its set point. The main result of this paper is the proposed *self-consistency rule* for evaluating the consistency of an inventory control system.

2.1 Introduction

One of the more elusive parts of process control education is inventory or material balance control. An engineer with some experience can usually immediately say if a proposed inventory control system is workable. However, for a student or newcomer to the field it is not obvious, and even for an experienced engineer there may be cases where the experience and intuition are not sufficient. The objective of this paper is to present concise results on inventory control, relate to previous work, tie up loose ends, and to provide some good illustrative examples. The main result (self-consistency rule) can be regarded as obvious, but nevertheless we have not seen them presented in this way before.

The main result is a simple rule to check whether an inventory control system is *consistent*. Here, consistency means that the mass balances for the entire plant are satisfied (Price and Georgakis, 1993). In addition, we usually want the inventory control system to be *self-consistent*. Self-consistency means that, in addition to plantwide consistency, the mass balance for each unit is satisfied by itself (locally), without the need to rely on control loops outside the unit. Consistency is a required property, because the mass balances must be satisfied in a plant, whereas self-consistency is a desired property of an inventory control system. In practice, an inconsistent control structure will lead to a situation with a fully open or closed control valve and the associated control loop cannot fulfill or attain the control set point.

In most plants, we want the inventory control system to use simple PID controllers and be part of the basic (regulatory) control layer. This is because it is generally desirable to separate the tasks of regulatory (stabilizing) control and supervisory (economic) control. From this it follows that the structure of the inventory control system is usually difficult to change later.

The importance of consistency of inventory control structures is often overlooked. Our work is partly inspired by the many examples of Kida, who has given industrial courses in Japan on control structures for many years. In a personal communication (Kida, 2008) he states that *"most process engineers, and even academic people, do not understand the serious problem of consistency of plantwide control configurations. When writing a paper, you have to clearly explain this point and make them convinced at the very outset. Otherwise they will not listen to or read through your detailed statements, but skip them all"*.

A very good early reference on inventory control in a plantwide setting is Buckley (1964). He states that material balance control must be in the direction of flow downstream a given flow and opposite the direction of flow upstream a given flow. Price and Georgakis (1993); Price *et al.* (1994) extended this and state that the inventory control must "radiate" outwards from the point of a given flow (throughput manipulator). As shown in this paper, all these statements are a consequence of requiring the inventory control system to be self-consistent.

Downs (1992) provides a very good discussion of material balance control in a plantwide control environment, with many clarifying examples. However, it is somewhat difficult for the reader to find a general rule or method that can be applied to new cases.

Luyben *et al.* (1997) propose a mainly heuristic design procedure for plantwide control. The procedure consist of, among others, "Step 6. Control inventories (pressures and levels) and fix a flow in every recycle loop", and possible limitations of this guideline are discussed in the present paper. Another guideline of Luyben *et al.* (1997) is to *"ensure that the overall component balances for each chemical species can be satisfied either through reaction or exit streams by accounting for the component's composition or inventory at some point in the process"*. As discussed later, this guideline is a bit limited because entrance (feed) streams is not considered.

Specific guidelines for designing inventory control structures are presented by

Georgakis and coauthors (Price and Georgakis, 1993; Price *et al.*, 1994). They propose a set of heuristic guidelines for inventory control design in a plantwide environment and also discuss consistency. The authors also state the importance of a self-consistent inventory control structure: "*Self-consistency appears to be the single most important characteristic governing the impact of the inventory control structure on system performance*".

As already mentioned, Fujio Kida from JGC Corporation in Japan has developed a lot of teaching material (Kida, 2008) and written several papers (e.g. Kida, 2004) on inventory control. Unfortunately, the work is published in Japanese only, but nevertheless it is clear that there are many detailed rules and some require detailed calculations. Our objective is to derive, if possible, a single rule for evaluating the consistency of inventory control system that applies to all cases and that only requires structural information.

The organization of the paper is as follows. First, we define self-consistent inventory control in Section 2.2. The main result in this paper is the self-consistency rule presented in Section 2.3. Thereafter, the rule is used to discuss consistency of flow networks in Section 2.4, which also discusses more specific rules that can be derived from the general self-consistency rule. Several examples in terms of inventory control are given in Section 2.5, before the paper is concluded in Section 2.6. Note that the present paper focuses on analysis of a fiven control structure. The design of the inventory control system, which in particular is related to the placement of the throughput manipulator, is discussed in more detail in a separate paper (Chapter 3).

Remark on notation: In this paper, when a flow is left unused or with a flow controller (FC), then this indicates that this flow is *not* used for inventory control. Instead the flow is either (1) used as a throughput manipulator (TPM), (2) given by another part of the plant (disturbance for our part), (3) fixed or (4) left as a degree of freedom for other control tasks. Also note that the general term used in this paper for an inventory controller is IC. This usually involves a level controller (LC) (liquid) or a pressure controller (PC) (gas).

2.2 Definition of self-consistent inventory control

The dynamic mass balance for total or component mass in any unit or process section can be written (e.g. Downs, 1992):

$$\text{Inflow} + \text{Generation} - \text{Outflow} - \text{Consumption} = \text{Change in inventory}$$

To keep the inventory within bounds, the change in inventory must be within bounds, and over long time (at steady-state) the change in inventory must be zero.

Thus, there must be a balance between the In-terms (inflow + generation) and Out-terms (outflow + consumption). However, without control this is not necessarily satisfied. The main objective of the inventory control system is to "stabilize" or provide "self-regulation" of all inventories such that the mass balances are satisfied. This leads to the self-consistency rule, which is the main result in this paper, but let us first defines some terms.

Definition 2.1. ***Consistency***. *An inventory control system is said to be* consistent *if the steady-state mass balances (total, components and phases) are satisfied for any part of the process, including the individual units and the overall plant.*

Remark. The use of mass balances for a phase may seem odd, and is discussed in more detail in the next section.

Since the mass balance must be satisfied for the overall plant, it follows that a consistent inventory control system must be *"able to propagate a production rate change throughout the process and in particular if such a change produces changes in the flow rates of major feed and product streams"* (Price and Georgakis, 1993).

Note that the above definition of consistency allows for "long loops" (not local loops) where, for example, the feed rate controls the inventory at the other end of the process (as illustrated in Figure 2.4). This is often undesirable and self-consistency is when the steady-state mass balances are satisfied also locally. More precisely, we propose the following definition:

Definition 2.2. ***Self-consistency***. *A consistent inventory control system is said to be* ***self-consistent*** *if there is* local *"self-regulation" of all inventories. This means that for each unit the* local *inventory control loops by themselves are sufficient to achieve steady-state mass balance consistency for that unit.*

Remark 1 "Self-regulation" here refers to the response of the process with its inventory control system in operation. If self-regulation is achieved without active control then this is referred to as "true" self-regulation.

Remark 2 The term "*local* inventory control loops" means that no control loops involving manipulated variables outside the unit are needed for inventory control of the unit (see Figure 2.4 for a system that does not satisfy this requirement).

Remark 3 The definitions require that the "steady-state mass balances" are satisfied. We are here referring to the *desired* steady-state, because an inconsistent inventory control system may give a steady-state which is not the desired one. For example, a component with no specified exit will eventually have to exit but this may not be a desired operation point.

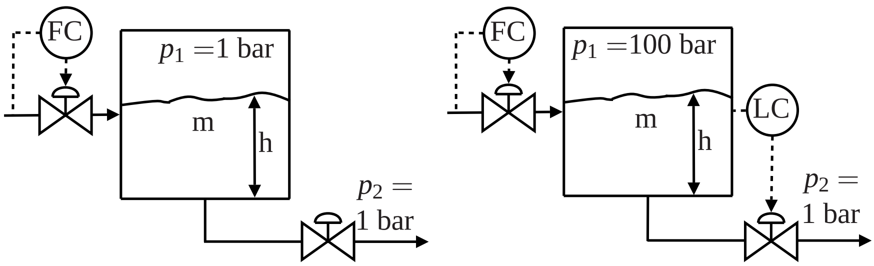
Example 2.1. ***Self-regulation.*** *"Self-regulation" may or may not require "active" control, as mentioned in Remark 1. As an example, consider regulation of liquid inventory (m) in a tank; see Figure 2.1(a). The outflow is given by a valve equation*

$$\dot{m}_{out} = C_v f(z)\sqrt{\Delta p \cdot \rho} \quad \text{[kg/s]}$$

where z is valve position. The pressure drop over the valve is

$$\Delta p = p_1 - p_2 + \rho g h$$

where h is the liquid level, which is proportional to the mass inventory, e.g., $m = h\rho A$ *for a tank with constant cross section area A. If the pressure drop* Δp *depends mainly on the liquid level h, then the inventory m is self-regulated. This is the case in Figure 2.1(a) where* $p_1 = p_2$ *so* $\Delta p = \rho g h$ *and the entire pressure drop over the valve is caused by the liquid level. Thus,* $\dot{m}_{out} \sim \sqrt{h}$*, which means that without control a doubling of the flow* $\dot{m}_{out}$ *will result an a four times larger liquid level (h). If this change is acceptable, then we have self-regulation. In other cases, it may be necessary to use "active" control to get sufficient self-regulation of the inventory. Specifically: In Figure 2.1(b),* $p_1 - p_2 = 99$ *bar so the relative pressure contribution from the liquid level (*$\rho g h$*) is much too small to provide acceptable self-regulation. For example, for a large tank of water with* $h = 10$ *m, the contribution from the level is only about 1 % (*$\rho g h \approx 1000$ *kg/m*$^3 \cdot$ *10 kg m/s*^{2} $\cdot$ *10 m =* 10^5 *N/m*^{2} *= 1 bar). In this case "active" control is required, where the level controller (LC) adjusts the valve position z, see Figure 2.1(b).*



(a) Self-regulation is possible without "active" control

(b) "Self-regulation" requires level control

Figure 2.1: Self-regulation of inventory in a tank with a given feed rate.

2.3 Self-consistency rule

As a direct consequence (implication) of the statements in Section 2.2, we propose the following rule to check if an inventory control system is self-consistent.

Rule 2.1. ***"Self-consistency rule":*** *Self-consistency (local "self-regulation" of all inventories) requires that*

1. *The total inventory (mass) of any part of the process must be "self-regulated" by its in- or outflows, which implies that at least one flow in or out of any part of the process must depend on the inventory inside that part of the process.*

2. *For systems with several components, the inventory of each component of any part of the process must be "self-regulated" by its in- or outflows or by chemical reaction.*

3. *For systems with several phases, the inventory of each phase of any part of the process must be "self-regulated" by its in- or outflows or by phase transition.*

Remark 1 A flow that depends on the inventory inside a part of the process, is often said to be on "inventory control". This usually involves a level controller (LC) (liquid) or pressure controller (PC) (gas), but it may also be a temperature controller (TC), composition controller (CC) or even no control ("true" self-regulation, e.g. with a constant valve opening).

Remark 2 The above requirement must be satisfied for "any part of the process". In practice, it is sufficient to consider individual units in addition to the overall process.

Remark 3 It is possible to extend the "self-regulation" rule to energy inventory, but this is not done here. We also doubt if such an extension is very useful, because in most cases the energy balance will maintain itself by "true" self-regulation (without control), for example because a warmer inflow in a tank leads to a warmer outflow.

Proof of self-consistency rule.

1. A boundary (control volume) may be defined for any part of the process. Let m [kg] denote the inventory inside the control volume and let $\dot{m}_{\text{in}}$ and $\dot{m}_{\text{out}}$ [kg/s] denote in- and outflows. Then the (total) mass balance is

$$\frac{dm}{dt} = \sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} \quad \text{[kg/s]}$$

   If $\dot{m}_{\text{in}}$ and $\dot{m}_{\text{out}}$ are independent (or weakly dependent) of the inventory m then this is an integrating (or close to integrating) process where m will not return to its desired steady-state (it will drift to an undesirable steady-state). To stabilize the inventory we must have "self-regulation" where $\dot{m}_{\text{in}}$ or $\dot{m}_{\text{out}}$ depends on the inventory (m), such that m is kept within given bounds in spite of disturbances. More precisely, $\dot{m}_{\text{in}}$ must decrease when m increases or $\dot{m}_{\text{out}}$ must increase when m increases, such that m is kept within given bounds in spite of disturbances.

2. Similarly, let n_A [mol A] denote the inventory of component A inside the control volume and let $\dot{n}_{A,\text{in}}$ and $\dot{n}_{A,\text{out}}$ [mol A/s] denote the in- and outflows. The mass balance for component A is

$$\frac{dn_A}{dt} = \sum \dot{n}_{A,\text{in}} - \sum \dot{n}_{A,\text{out}} + G_A \quad \text{[mol A/s]}$$

where G_A is the net amount generated by chemical reaction. Again, if $\dot{n}_{A,\text{in}}$, $\dot{n}_{A,\text{out}}$ and G_A are independent (or weakly dependent) of the inventory n_A then this is an integrating (or close to integrating) process where n_A will not return to its desired steady-state. To stabilize the inventory we must have "self-regulation" where $\dot{n}_{A,\text{in}}$, $\dot{n}_{A,\text{out}}$ or G_A depend on n_A such that n_A is kept within given bounds in spite of disturbances.

An example where the inventory n_A is self-regulated because of the reaction term G_A is the irreversible reaction $A+B \rightarrow P$, where B is in excess and A is the limiting reactant. In this case, an increase in inflow of A ($\dot{n}_{A,\text{in}}$) will be consumed by the chemical reaction.

3. The rule for the individual phase follows by simply defining the control volume as the parts of the process that contain a given phase P and applying the mass balance to this control volume. Let m^P [kg] denote the inventory of the given phase inside the control volume and let $\dot{m}^P{}_{\text{in}}$ and $\dot{m}^P{}_{\text{out}}$ [kg/s] denote the in- and outflows. The mass balance for a given phase is then

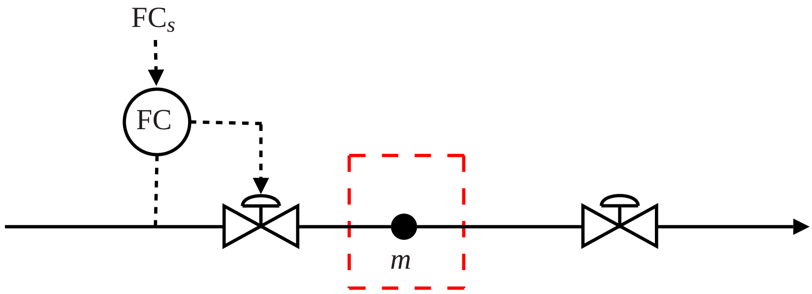
$$\frac{dm^P}{dt} = \sum \dot{m}^P_{\text{in}} - \sum \dot{m}^P_{\text{out}} + G^P \quad \text{[kg/s]}$$

where G^P is the net phase transition over the phase boundary. If $\dot{m}^P_{\text{in}}$, $\dot{m}^P_{\text{out}}$ and G^P are independent (or weakly dependent) of the inventory then this is an integrating (or close to integrating) process where m^P will not return to its desired steady-state. To stabilize the inventory we must have "self-regulation" where $\dot{m}^P_{\text{in}}$, $\dot{m}^P_{\text{out}}$ or G^P depends on the inventory (m^P) such that m^P is kept within given bounds in spite of disturbances.

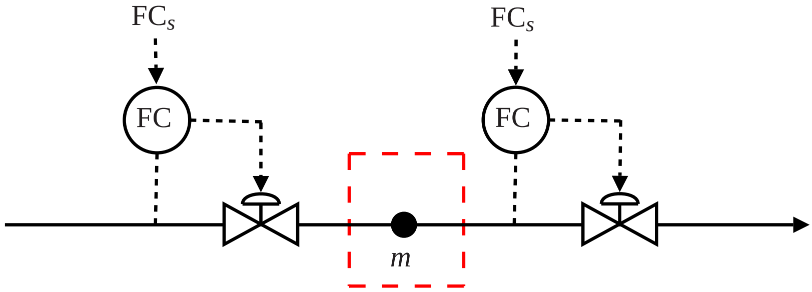
An example where we need to consider individual phases is a flash tank where a two-phase feed is separated into gas and liquid.

□

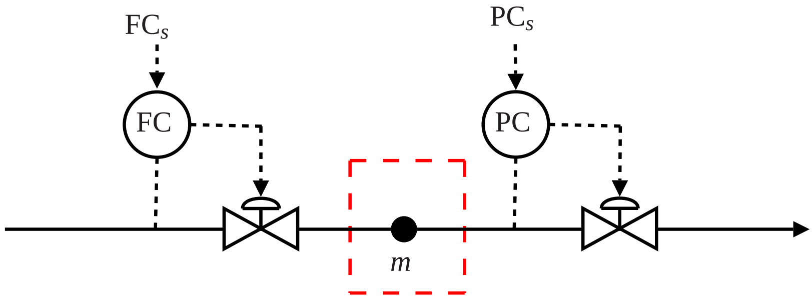
Example 2.2. ***Stream with two valves.*** *To demonstrate the self-consistency rule on a very simple example, consider a single stream with two valves; see Figure 2.2(a). There is only a single (small) hold-up m in this simple process (illustrated by the big dot), so consistency and self-consistency are here the same. The pressure p depends directly on the inventory m (for a liquid the dependency is very strong; for an ideal gas it is* $p = \frac{mRT}{V}$*). Thus, self-regulation of inventory is the same as self-regulation of pressure. To apply the self-consistency rule, we define a control volume (dotted box) as shown in Figure 2.2 and note that the inflow is om flow control in all four cases, that is, the inflow is independent of the*



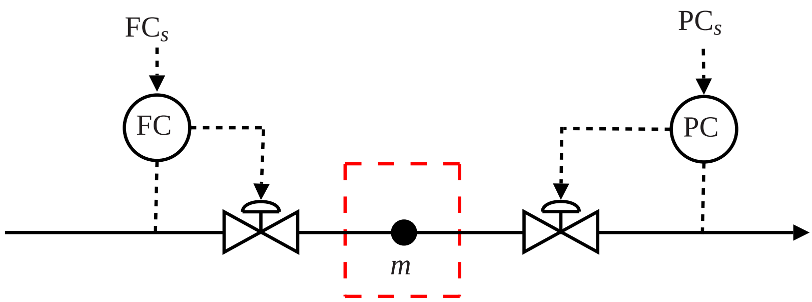
(a) OK (consistent control structure since outflow depends on invneotry m)



(b) Not consistent control structure since outflow is fixed



(c) OK (consistent control structure since outflow depends on inventory m)



(d) Not consistent control structure since outflow does not depend correcltry on inventory m

Figure 2.2: Four different control structures for stream with two valves.

inventory m. Thus, according to Rule 2.1, to have consistency (self-regulation), the outflow must depend on the pressure p (inventory m) and more specifically the outflow must increase when p increases.

Four different control structures are displayed in Figure 2.2. According to Rule 2.1, the structure in Figure 2.2(a) is consistent since the outflow depends on the pressure p (inventory m). Thus, we have "true" self-regulation with no need for active control.

The control structure in Figure 2.2(b) is not consistent because the outflow is independent on the inventory m. Even if the set points to the two flow controllers were set equal, any error in the actual flow would lead to an imbalance, which would lead to accumulation or depletion of mass and the inventory would not be self-regulated.

The structure in Figure 2.2(c) is consistent because the outflow depends on the pressure (inventory m).

Finally, the control structure in Figure 2.2(d) is not consistent because the outflow depends on the inventory m (and pressure) in the wrong (opposite) manner. To understand this, consider a decrease in inflow, which will lead to a decreased pressure in the control volume. A lower differential pressure over the pressure-controlled valve leads to a smaller flow through the valve and the pressure at the downstream measuring point will decrease, leading the pressure controller to open *the valve. The result a further pressure decrease in the control volume, so the pressure controller is actually working in the wrong direction. The opening of the pressure-controlled calve will also affect the flow-controlled valve and, depending on the set point of the controllers, either the flow-controlled valve or the pressure-controlled valve will move to fully open. The other pressure-controlled valve or flow-controlled valve will continue to control pressure or flow. It should also be noted that the pressure control loop is in the direction* opposite *to flow, which is not correct when the inflow is given (see further discussion in Section 2.4.1).*

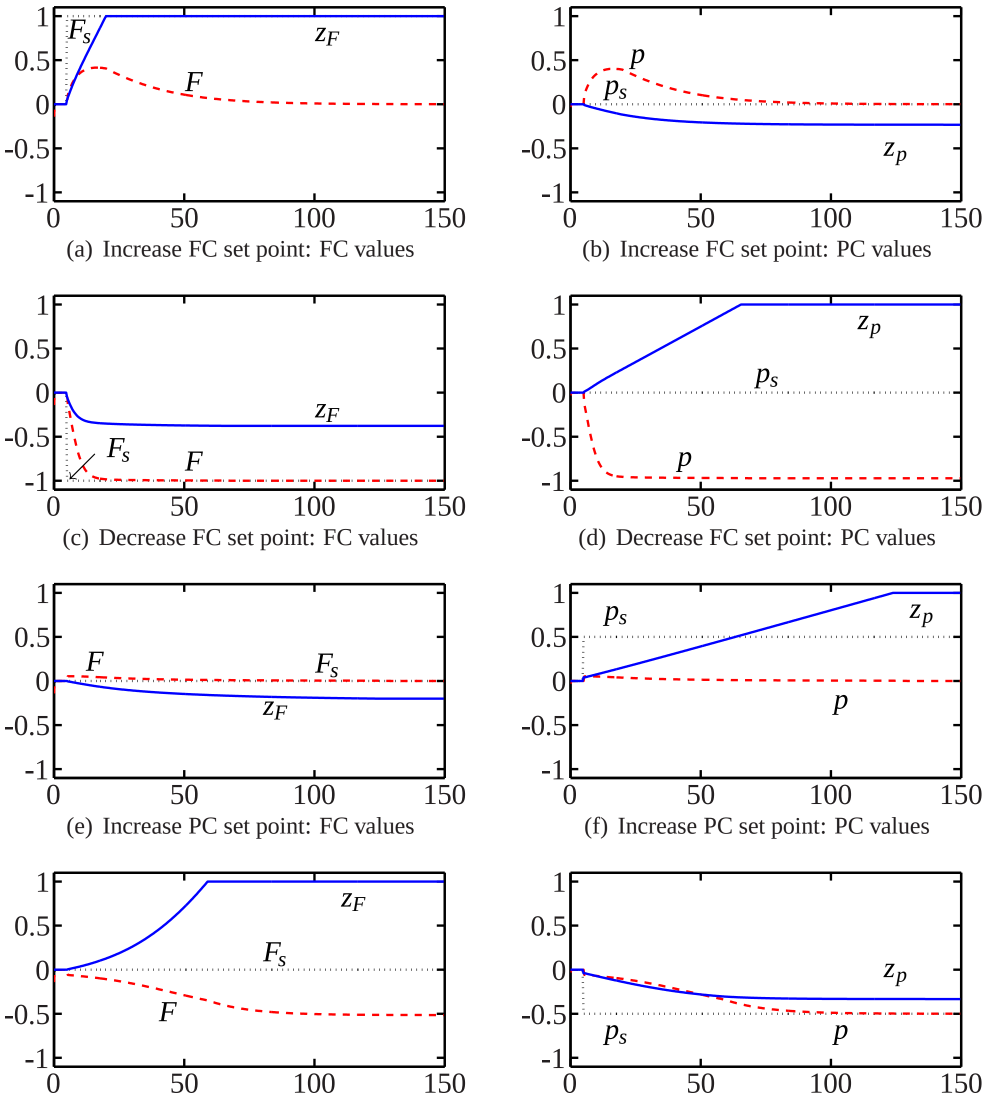
Dynamic simulations of the simple configuration in Figure 2.2(d) using a dynamic flowsheet simulator (Aspen HYSYS®) are shown in Figure 2.3:

10% increase in FC set point: *The FC saturates at fully open and the PC maintains its set point (Figures 2.3(a) and 2.3(b)).*

10% decrease in FC set point: *The FC maintains its set point and the PC saturates at fully open (Figures 2.3(c) and 2.3(d)).*

5% increase in PC set point: *The FC maintains its set point and the PC saturates at fully open (Figures 2.3(e) and 2.3(f)).*

5% decrease in PC set point: *The FC saturates at fully open and the PC maintains its set point (Figures 2.3(g) and 2.3(h)).*



(a) Increase FC set point: FC values
(b) Increase FC set point: PC values
(c) Decrease FC set point: FC values
(d) Decrease FC set point: PC values
(e) Increase PC set point: FC values
(f) Increase PC set point: PC values
(g) Decrease PC set point: FC values
(h) Decrease PC set point: PC values

Figure 2.3: Dynamic simulations of the simple configuration in Figure 2.2(d). Left column: Flow controller. Right column: Pressure controller. In all cases, one of the valves move to fully open.

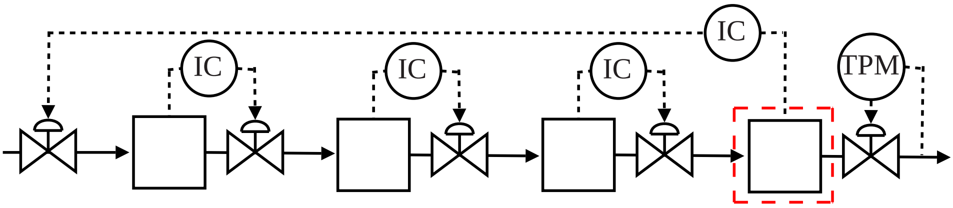


Figure 2.4: Consistent, but not self-consistent inventory control structure.

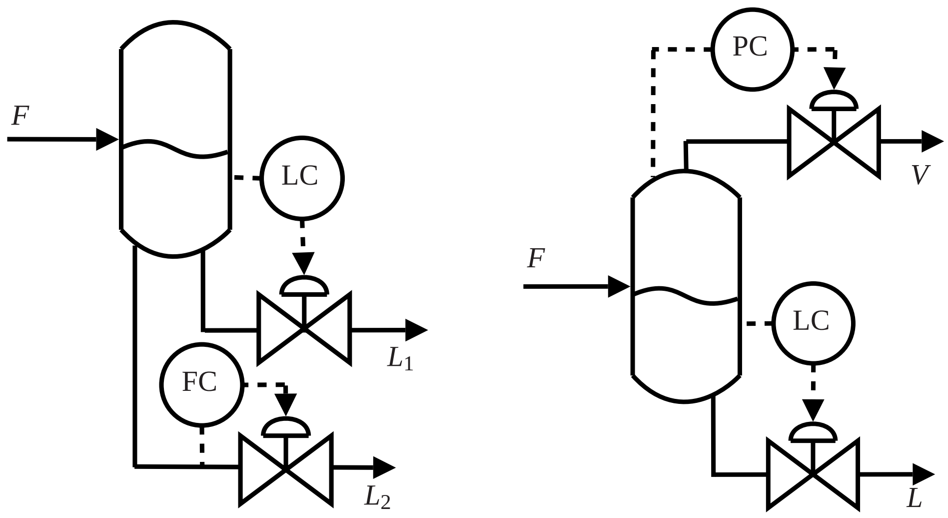
A remark about the sign of the controller needed to obtain a negative feedback loop: Opening a valve increases the flow, so a flow controller is always "reverse acting" with a negative feedback sign. The sign of inventory controllers for level and pressure depend on the location of the valve relative to the inventory (level or pressure). If control is in the direction of flow (with the inventory measurement for level or pressure upstream the valve) then the controller must be "direct acting"; if control is in opposite direction of flow then it must be "reverse acting". These rules where used when tuning the controllers in Figures 2.2 and 2.3.

Example 2.3. ***Units in series.*** *To understand the difference between the terms consistency (Definition 2.1) and self-consistency (Definition 2.2), consider inventory control of the series process in Figure 2.4. The control structure is* consistent *and is able to propagate a production rate change to a change in the feed rate. However, the in- and outflows for the last unit (dashed box) do not depend directly on the inventory inside the unit and the control volume is therefore* not self-consistent. *This can also be seen because the inventory controllers are not in the direction opposite to flow as they should be for a process with a given product rate (see also Section 2.4.1). To make the structure consistent it is necessary to introduce a "long loop" where the inflow of the first unit is used to control the inventory in the last unit.*

Example 2.4. ***Phase transition***. *In some cases, phase transition needs to be considered for self-consistency. Consider Figure 2.5 where the inflow is given. Thus, according to Rule 2.1, to have consistency the outflow must depend on the inventory in the tank.*

In Figure 2.5(a), the inlet is a single (liquid) phase and the outlet from the single-phase tank is split in two streams (L_1 and L_2). This split is adjustable and represent a degree of freedom. Hence, one of the outlets must be on inventory control whereas the other outlet can be flow controlled. This follows because an adjustable split introduces an extra degree of freedom, but the number of inventories that need to be controlled are unchanged.

In Figure 2.5(b) there are two phases that needs to be controlled, both the gas and the liquid phase. To have a consistent inventory control structure, both



(a) Adjustable split: Single-phase tank (b) Fixed split: Two-phase tank

Figure 2.5: Adjustable split introduces a degree of freedom but a phase transition requires that all phases are on inventory control.

a gas and liquid stream must be on inventory controlled. In Figure 2.5(b) this is illustrated by the LC and PC. In this case, the split is not actually an extra degree of freedom because the split is indirectly determined by the feed composition to the flash tank (separator). This demonstrates that each phase must be considered to ensure self-consistency.

2.4 Specific rules and consistency of flow networks

In a flow network there is at least one degree of freedom, called the throughput manipulator (TPM), which sets the network flow. More generally, *a TPM is a degree of freedom that affects the network flow, and which is not directly or indirectly determined by control of the individual units, including inventory control* (see Chapter 3). Typically, a fixed flow (flow controller with given set point) is a TPM. As discussed in more detail below, the location of the TPM is very important. After the placement of the TPM has been made, and if there are no splits or junctions, there is only one *self-consistent* inventory control system. However, at splits (e.g. multiple products) or junctions (e.g. multiple feeds), there are several possibilities.

At a split or junction, a common choice is to use the largest flow for inventory control (Luyben *et al.*, 1997). For example, with a given feed, the largest product stream may be used for inventory control with the flow rates of the smaller product streams used for quality control. Similarly, with a given production rate, the largest feed rate is often used for inventory control and the smaller feed flows are set in ratio relative to this, with the ratio set point possibly used for quality control.

The objective is now to apply the Consistency Rule to analyze inventory control structures for real processes (flow networks). We consider three network classes:

1. Units in series
2. Recycle systems
3. Closed systems

A series network may have splits, provided the flow is still in the same direction. Note that each split introduces one extra degree of freedom (the split ratio). Recycle systems contains one or more splits that are (partly) fed back to the system. A closed system has total recycle with no feeds or products.

2.4.1 Units in series ("radiating rule")

As mentioned above, if there are no splits or junctions, the location of the throughput manipulator determines the self-consistent inventory control system. Specifically, a direct consequence of the self-consistency rule is

- *Inventory control must be in direction of flow downstream the location of a fixed flow (TPM).*
- *Inventory control must be in direction opposite to flow upstream the location of a fixed flow (TPM).*

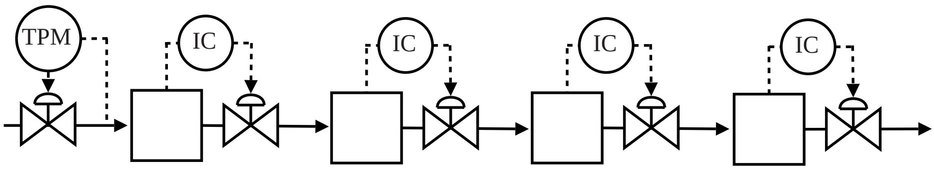
More generally, we have:

Rule 2.2. ***Radiation rule*** *(Price and Georgakis, 1993): A self-consistent inventory control structure must be radiating around the location of a fixed flow (TPM).*

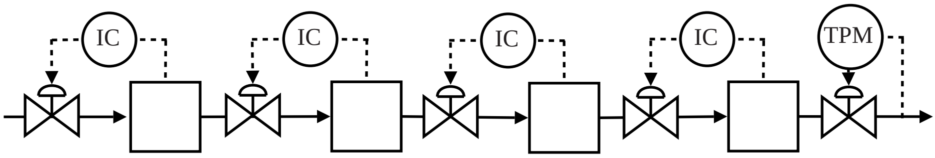
These rules are further illustrated in Figure 2.6.

2.4.2 Recycle systems

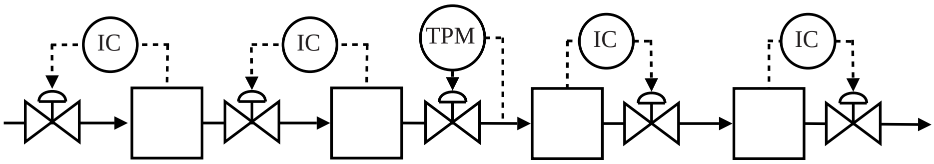
A recycle system usually has an adjustable split, which (but not always) *introduces an extra degree of freedom for control of the network flow* (Kida, 2008). On the other hand, the requirement of self-consistency imposes limitations. As an example, consider the simple recycle example with a fixed feed and an adjustable split in



(a) TPM at inlet (feed): Inventory control in direction of flow.



(b) TPM at outlet (on-demand): Inventory control in direction opposite to flow



(c) General case with TPM inside the plant: Radiating inventory control

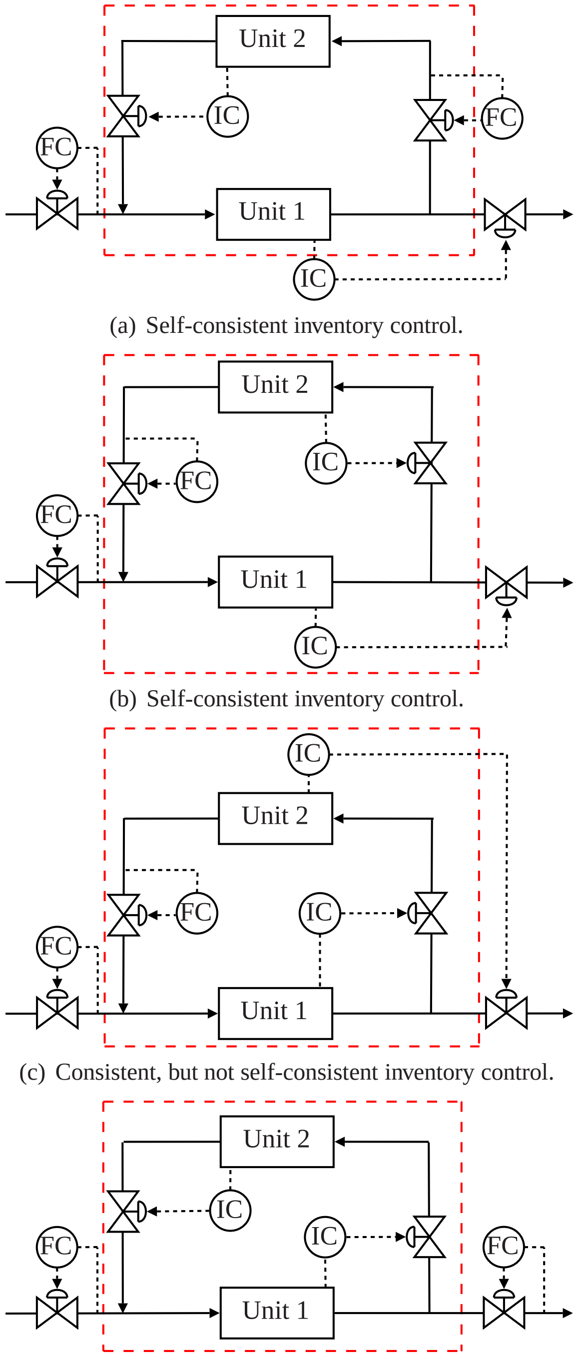
Figure 2.6: Self-consistency requires a radiating inventory control around a fixed flow (TPM)

Figure 2.7 (there is a pump or compressor in the recycle loop which is not shown). Figures 2.7(a) and 2.7(b) have a consistent inventory control structure, because the outflows from units 1 and 2 depend on the inventory inside. In both cases one flow in the recycle loop is fixed (flow controlled and the flow set point may be used for other purposes than inventory control). Note that *the inventory control in the recycle loop can be either in direction of flow* (Figure 2.7(a)) or *direction opposite to flow* (Figure 2.7(b)), because the flow rate can be fixed at any location in the recycle loop.

In Figure 2.7(c) the inventory loops for units 1 and 2 are paired opposite. This structure is not self-consistent because the inventory of unit 2 is not "self-regulated by its in- or outflows" and thus violates Rule 2.1. In addition, the inventory control of unit 2 requires that other inventory loop is closed, and thus violates Definition 2.2.

Finally, Figure 2.7(d) is obviously not consistent since both the feed rate and the product rate are fixed. In particular, the inflow and outflow to the dotted box do not depend on the inventory inside this part of the process, which violates Rule 2.1.

Remark. This simple example seems to prove the rule that "*one flow rate somewhere in the recycle loop should be flow controlled*" (Luyben, 1993*c*). This rule follows because there is an extra degree of freedom introduced by the split, but the number of inventories



(a) Self-consistent inventory control.

(b) Self-consistent inventory control.

(c) Consistent, but not self-consistent inventory control.

(d) Not consistent inventory control.

Figure 2.7: Inventory control of simple recycle process.

that need to be controlled are unchanged. However, a counter example is provided by the self-consistent reactor-separator-recycle process in Figure 2.11(a). In this case, the split is not actually an extra degree of freedom because the split is indirectly determined by the feed composition to the separator (distillation column), as discussed in Example 2.4.

2.4.3 Closed systems

Closed systems require particular attention. It is clear from the total mass balance that the total inventory of a closed system cannot be self-regulated since there are no in- or out streams. Thus, our previously derived rule (Rule 2.1) does not really apply. As an example, consider a closed system with two inventories. In Figure 2.8(a) we attempt to control both inventories, but the two loops will “fight each other” and will drift to a solution with either a fully open or fully closed valve. For example, a (feasible) solution is to have zero flow in the cycle. The problem is that the flow is not set anywhere in the loop. To get a consistent inventory control structure, *one must let one of the inventories be uncontrolled*, as shown in Figures 2.8(b) and 2.8(c). *The corresponding unused degree of freedom (flow) sets the flow rate (“load”, throughput) of the closed system.*

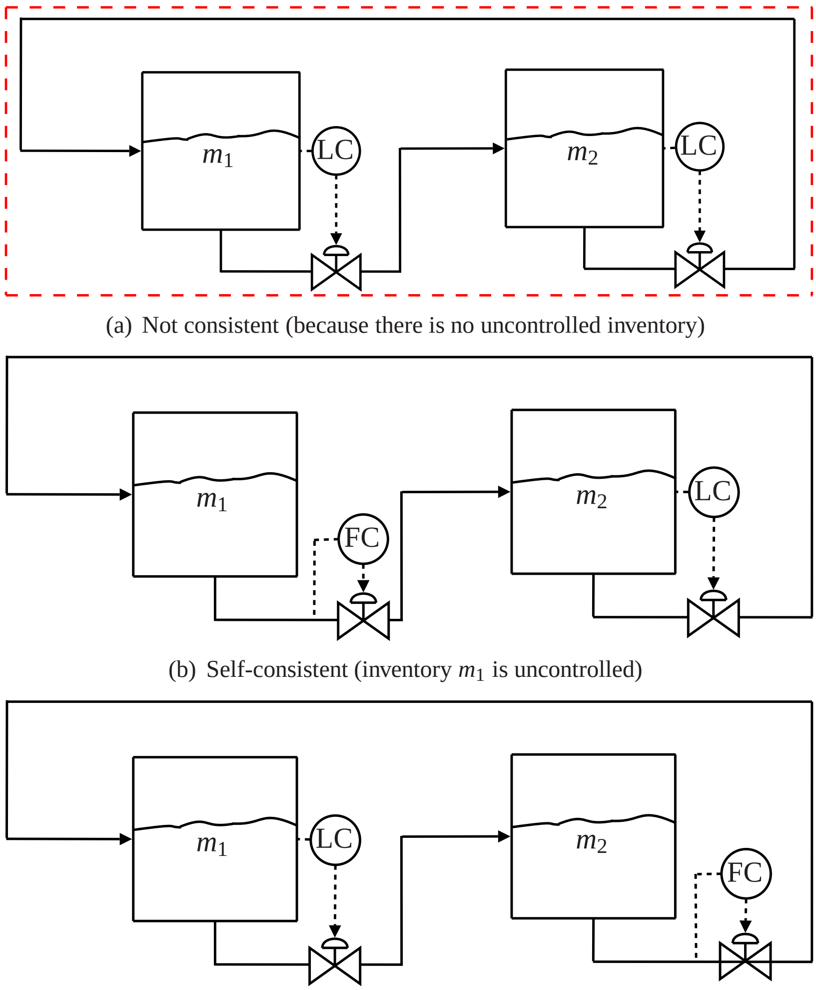
For closed systems there are two alternative “fixes” for our self-consistency rule (Rule 2.1:

1. Let the total inventory be uncontrolled (*not* self-regulated), which is how such systems are usually operated in practice. Typically the largest single inventory is uncontrolled. However, the remaining inventories must be self-regulated, as usual, to have self-consistency of the inventory control system.

2. Introduce a “dummy” stream that keeps the total inventory constant. This corresponds to allowing for filling (charging) or emptying the system. In practice, this stream may be a make-up stream line that refills or empty the largest inventory, e.g. on a daily or monthly basis.

Both approaches allow for disturbances, such as leaks or supply. The inventory control system can then be analyzed using the normal self-consistency rule (Rule 2.1). Figure 2.8(a) is clearly not allowed by Fix 1 as the total inventory is not left uncontrolled. Figure 2.8(a) is also not consistent by Fix 2, since for self-consistency the dummy stream must be used for inventory control instead of one of the two flows in the recycle loop.

Example 2.5. ***Absorber-regenerator example.*** *In this example, the consistency rule (Rule 2.1) is used for an individual phase. Consider the absorber and regenerator example in Figure 2.9 (Kida, 2008) where a component (e.g. CO_2) is removed from a gas by absorption. The inlet gas flow (feed) is indirectly given*



(a) Not consistent (because there is no uncontrolled inventory)

(b) Self-consistent (inventory m_1 is uncontrolled)

(c) Self-consistent (inventory m_2 is uncontrolled)

Figure 2.8: Inventory control for closed system.

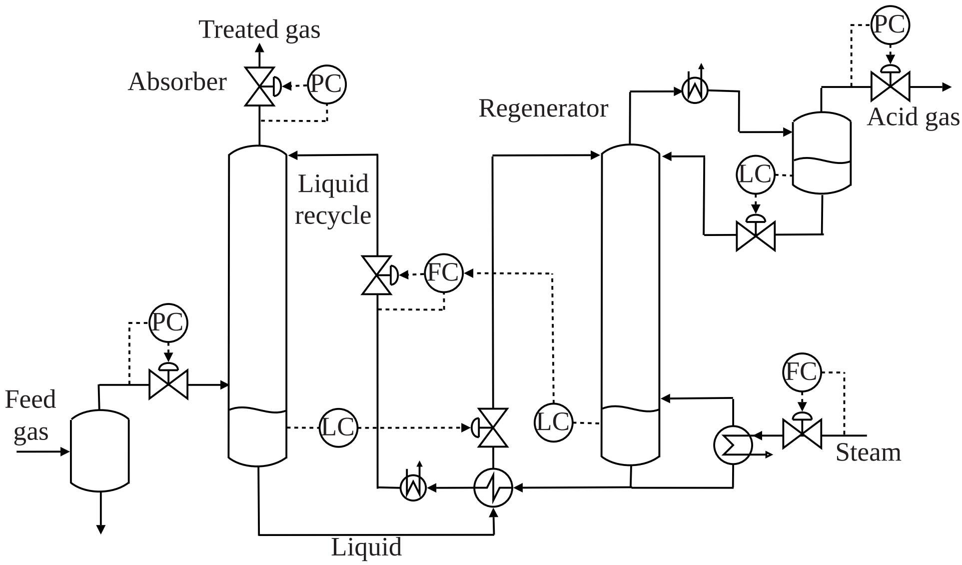


Figure 2.9: Absorber and regenerator example: Not consistent liquid inventory control (from Kida (2008)).

because there is a pressure control in the direction of flow at the inlet. The gas outlet flows are on pressure control in the direction of flow and thus depend on the gas holdup in the plant. Therefore the gas phase inventory control is consistent. However, the liquid flows between the absorber and regenerator make up a "closed system" (expect for minor losses). There is a flow controller for the recycled liquid, but its set point is set by the inventory in the regenerator, hence all inventories in the closed system are on inventory control, which violates the rule just derived. To get a consistent inventory control structure, we must break the level-flow cascade loop and let the inventory in the bottom of the regenerator remain uncontrolled.

2.4.4 Summary of specific rules

In the literature there are many rules that deal with inventory control structure. In addition to the radiating rule, some useful rules that can be developed from the self-consistency rule are:

1. *All systems must have at least one given flow (throughput manipulator).*

Proof. Assume there is no throughput manipulator. Then all flows must be on inventory control, which will not result in a unique solution. For example, zero flow will be an allowed solution. □

2. *Component balance rule (Downs, 1992, p. 414): Each component, whether important or insignificant, must have its inventory controlled within each unit operation and within the whole process.* Luyben *et al.* (1998, p. 56) refers to this as "Downs drill".

   Proof. This comes from the requirement of component self-consistency (Rule 2.1). □

3. *A stream cannot be flow controlled more than once, that is, a structure with two flow controllers on the same stream is not consistent.*

   Proof. Make a control volume with the two flow-controlled streams as in- and outflows. Then neither the inflow nor the outflow depends on the control volume and the inventory is not self-regulated. This is demonstrated in Figure 2.2(b). □

4. *Price and Georgakis (1993, p.2699): If a change in the throughput manipulator does not result in a change in the main feed flow, then the control structure is inconsistent.*

   Proof. This follows from the requirement of satisfying the steady-state mass balances. □

5. *Generalized from Price and Georgakis (1993, p.2699): A self-consistent inventory control structure must use the feed or the product (or both) for inventory control.*

   Proof. This follows from the steady-state mass balance. This is also discussed in Section 2.4.1 and a clear illustration of this statement is found in Figure 2.6. □

6. *For closed systems: One inventory must be left uncontrolled and one flow in the closed system must be used to set the load.*

   Proof. This follows from that all systems must have at least one given flow to be unique. To be able to fix the load for a closed system, one inventory must be uncontrolled. □

The rules are summarized by the proposed procedure for inventory control system design in Table 2.1, which is inspired by the inventory control guidelines in Price *et al.* (1994).

1	Choose the location of the throughput manipulator
2	Identify inventories that need to be controlled including: a) Total mass b) Components c) Individual phases
3	Identify manipulators suitable for adjusting each inventory
4	Design a self-consistent radiation inventory control system that controls all the identified inventories. This means: a) Inventory control in direction of flow downstream the throughput manipulator b) Inventory control in direction opposite to flow upstream the throughput manipulator
5	At junctions or splits a decision has to be made on which flow to use for inventory control. Typically, the largest flow is used, or both streams are changed such that their ratio is held constant (often the ratio is set by a slower outer composition loop).
6	Recycles require special consideration. Make a block (control volume) around the entire section and make sure that there is self-consistency for total mass, (individual) components and phases (if relevant).
7	Assign control loops for any process external flow that remain uncontrolled. Typically, "extra" feed rates are put on ratio control with the ratio set point being set by an outer composition loop.

Table 2.1: Proposed guidelines for design of self-consistent inventory control system. In case of doubt consult the general self-consistency rule (Rule 2.1).

2.5 Examples

In this section we demonstrate the self-consistency rule on some well known examples from the academic literature.

2.5.1 Distillation column with DB-configuration

An example of a recycle system is a distillation column. As seen from Figure 2.10, a distillation column has one split in the condenser (V_T splits into L and D) and one split in the reboiler (L_B splits into B and V). In both cases one of the streams is recycled to the column (L and V, respectively). The two splits introduce two degrees of freedom and this gives rise to many possible inventory control structures ("configurations"), as has been discussed widely in the literature (see e.g. Skogestad (2007) for a summary of this discussion).

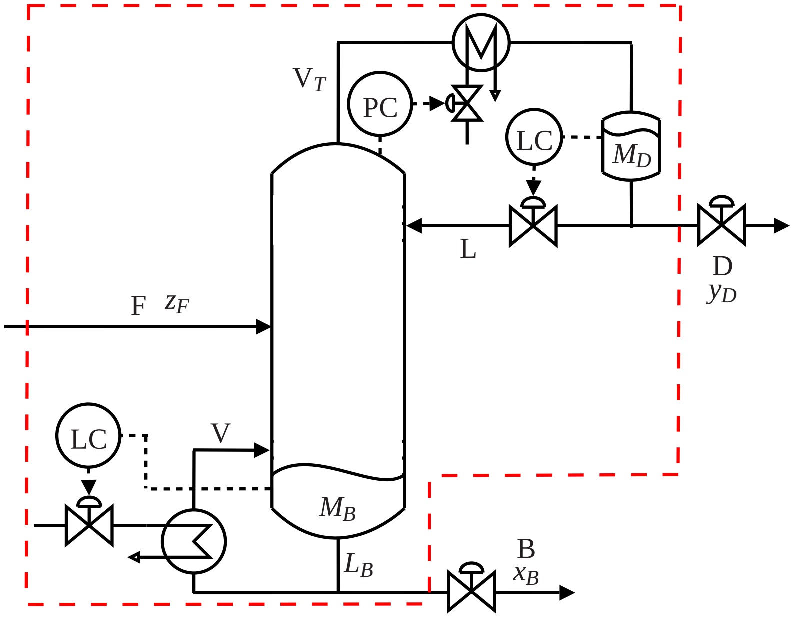


Figure 2.10: Example of inconsistent inventory control at recycle process: Distillation column with DB-configuration.

Figure 2.10 displays the DB-configuration, which uses reflux L and boilup V for inventory control (condenser and reboiler level control), such that D and B remain as degrees of freedom for other purposes (e.g. on flow control). The DB-configuration has earlier been labeled "impossible", "unacceptable" or "infeasible" by distillation experts (e.g. Perry and Chilton 1973, p.22-123; Shinskey 1984, p.154). This inventory control system also violates Luybens rule of "fixing a flow in the recycle loop" and it is indeed true that this inventory control system is not self-consistent. To see this, consider the dashed box in Figure 2.10 where we note that none of the flows in or out of the column (F, D and B) depend on the inventory inside the column. However, an inconsistent inventory control system can usually be made consistent by adding control loops and the DB-configuration is workable (and consistent) provided one closes at least one extra loop, for example by using D to control a temperature inside the column (Finco *et al.*, 1989; Skogestad *et al.*, 1990). Thus, labeling the DB-configuration as "impossible" is wrong. In summary, the DB-configuration can be made consistent by adding a temperature (or composition) control loop, but it is not self-consistent.

Remark 1 An example of a self-consistent inventory control structure for distillation is the common LV-configuration, where the two level loops have been interchanged such that D and B are used for level control and L and V remain as degrees of freedom (e.g. on flow control). In the LV-configuration, inventory is controlled in the direction of flow.

Remark 2 An additional inventory issue for distillation columns is related to the split between light and heavy components (component inventory). One may regard the column as a "tank" with light component in the upper part and heavy in the lower part. Thus, one is not really free to set the split between D and B and to avoid a "drifting" composition profile (with possible "breakthrough" of light component in the bottom or of heavy component in the top), one must in practice close a quality (e.g., temperature or pressure) loop to achieve component self-consistency (Skogestad, 2007). For example, for the LV-configuration one may use the boilup V to control a temperature inside the column. This consideration about controlling the column profile also applies to the DB-configuration. Thus, in practice, the DB-configuration requires closing *two* quality loops to maintain mass and component balances. This means that both D and B are used for quality control for the DB-configuration, rather than only one (L or V) for the LV-configuration.

2.5.2 Reactor-separator-recycle example with one reactant

A common recycle example in the academic literature is the reactor-separator-recycle system in Figure 2.11. The system has a continuous stirred-tank reactor (CSTR) with an irreversible, isothermal, first order reaction $A \rightarrow B$, followed by separation (distillation) and recycle of the unreacted feed component back to the reactor (e.g. Luyben 1993*a*,*b*; Price and Georgakis 1993; Larsson *et al.* 2003).

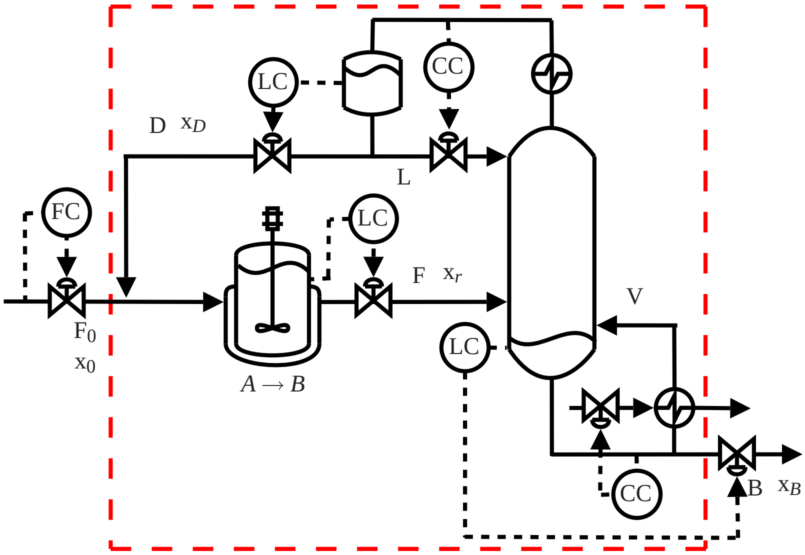
The feed (F_0) is pure reactant A and the component mass balances become

$$\text{Component A:} \quad F_0 = \underbrace{k(T) \cdot x_{r,A} \cdot V}_{-G_A = G_B} + B \cdot x_{B,A}$$

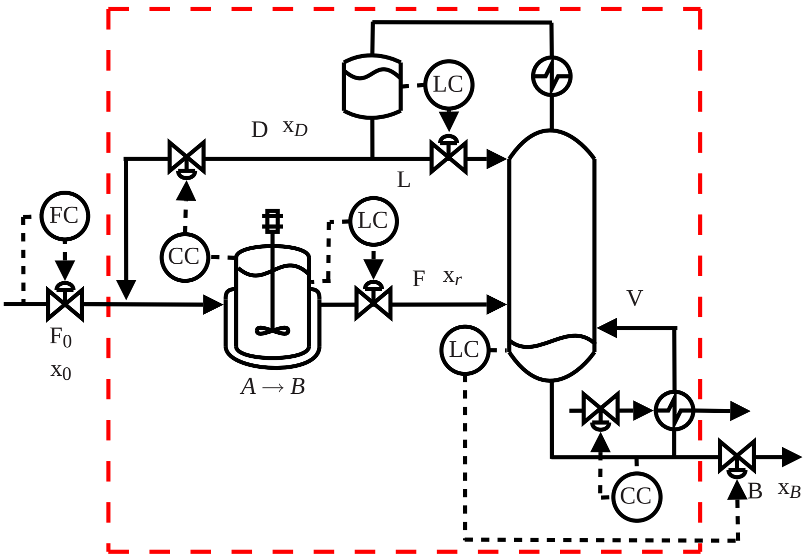
$$\text{Component B:} \quad \underbrace{k(T) \cdot x_{r,A}}_{G_B} = B \cdot x_{B,B}$$

where x is the mole fraction, V is the reactor volume and $k(T)$ is the reaction rate constant. Note that $B = F_0$ [mol/s] at steady-state. Component A enters the process in the feed stream and most of it is consumed in the reactor. The inventory of component A is therefore expected to be self-regulated by the reaction. Component B is produced in the reactor (G_B) and exits the process in stream B. Component B is not self-regulated by the reaction and requires a controller to adjust its inventory.

Two different control structures for the reactor-separator-recycle process are displayed in Figure 2.11. Both have fixed feed (F_0) and inventory control is the direction of flow. Thus, both of them are self-consistent in total mass, because the outflow B form the process depends on the inventory inside the process (indicated by the dashed control volume) (Rule 2.1). Since the outflow B mainly consist of component B, this implies that both structures are also consistent (self-regulated) with respect to the inventory of component B. The difference between the two



(a) Conventional: Self-consistent inventory control structure.



(b) Composition control of reactor composition: Not consistent for component *A*.

Figure 2.11: Reactor-separator-recycle process with one reactant (A).

structures is related to the control of component A. The "conventional" structure in Figure 2.11(a) uses the LV-configuration for the distillation column where the reflux (L) controls the composition in the recycle (distillate) D. The structure in Figure 2.11(b) uses the DV-configuration for the column where the reactor composition $x_{r,A}$ is controlled instead of the recycle (distillate) composition.

As already mentioned, the inventory of component A is expected to be self-regulated by the reaction $A \rightarrow B$, so one would expect both structures to be consistent with respect to component A. In fact, both structures would be consistent if one *removed* the composition loop tn the recycle loop (thus, fixing reflux L in Figure 2.11(a) and fixing recycle D in Figure 2.11(b)). With the composition loop closed, the "conventional" structure in Figure 2.11(a) remains consistent, but not the structure with control of reactor composition in Figure 2.11(b). The reason for the inconsistency is that control of reactor composition eliminated the self-regulation by reaction: The amount of A that reacts is given by $-G_A = G_B = k(T)x_{r,A}V$ and with fixed $x_{r,A}$ (because of the controller), T and V there is no self-regulation. The inconsistency of this control structure is pointed out by e.g. Downs (1992) and Luyben (1994).

Remark 1 The control structures in Figure 2.11 would both be self-consistent without closing the composition loop in the recycle. The reason for closing this composition loop is therefore not for consistent inventory control but rather for other (economic) reasons (Larsson *et al.*, 2003). The interesting point to note, is that cosing an extra loop can in some cases make the system inconsistent.

Remark 2 Luyben (1994) has proposed to make the system in Figure 2.11(b) consistent by introducing an adjustable reactor volume, but this is not a good solution, because we always want to use the maximum reactor volume for economic reasons (energy saving) (Larsson *et al.*, 2003).

Remark 3 The inventory of component A is expected to be self-regulated by the reaction $A \rightarrow B$. More precisely, the amount that reacts is $-G_A = kx_{r,A}V$ and the composition $x_{r,A}$ will "self-regulate" such that at steady-state $F_0 \approx -G_A$, that is, $x_{r,A} \approx F_0/(kV)$.

Remark 4 We already noted that fixing $x_{r,A}$ (Figure 2.11(b)) breaks this self-regulation and makes the system inconsistent. A related problem is when the reactor volume V is too small relative to the feed F_0, such that the required $x_{r,A}$ exceeds 1, which is impossible. In practice, if we increase the feed rate F_0 and approach this situation, we will experience "snow-balling" (Luyben, 1993*c*) where the recycle D becomes very large, and also the boilup V becomes very large. Eventually, V may reach its maximum value, and we loose composition control and we will get "break-through" of A in the bottom product.

Remark 5 Consider the same process (Figure 2.11), but assume that the fresh feed (F_0) contains an inert component I in addition to the reactant A. If I is more volatile than component B, then component I will be recycled back to the reactor and will accumulate in the process. None of the inventory control systems in Figure 2.11 are consistent for the inert I.To make the system self-consistent for the inert, a purge stream must be introduced where part of stream D is taken out as a by-product.

2.5.3 Reactor-separator-recycle process with two reactants

Another well studied recycle example is a reactor-separator-recycle process where two reactants A and B reacts according to the reaction $A+B \rightarrow C$ (e.g. Tyreus and Luyben, 1993). Component B is the limiting reactant as the recycle D contains mostly component A. Two different control structures are displayed in Figure 2.12. In both cases the distillate flow D (recycle of A) is used to control the condenser level (main inventory of A).

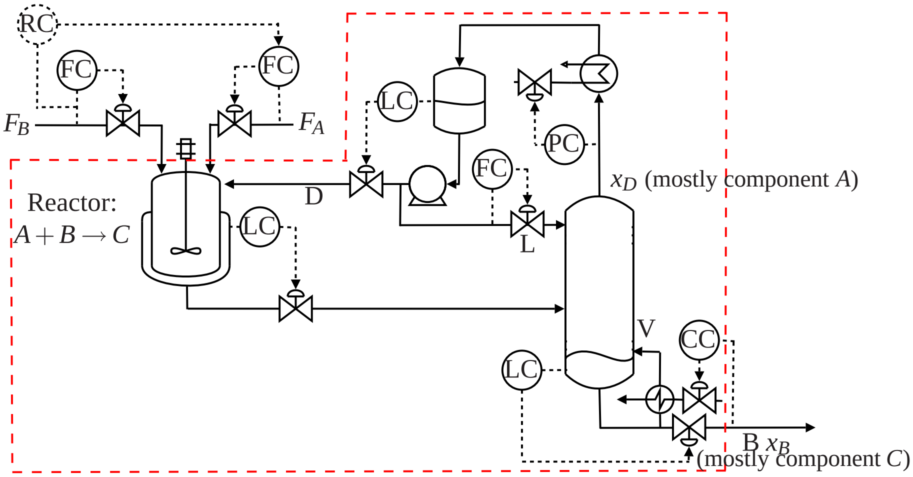
In Figure 2.12(a), both fresh reactant feeds (F_A and F_B) are flow controlled into the reactor, where reactant A is set in ratio to reactant B such that $F_A/F_B = 1$. This control strategy is not consistent because it not possible to feed exactly the stoichiometric ratio of the two reactants (Luyben *et al.*, 1998, p.37). Any imbalance will over time leas to a situation where the recycle of A either goes towards zero or towards infinity.

To get a consistent inventory control structure, the first requirement is that one of the feed rates (F_A or F_B) must be dependent on what happens inside the process, such that we at steady-state can achieve $F_A = F_B$. One solution is to fix F_B (the limiting reactant) and adjust F_A such that the desired excess of A is achieved, resulting in the self-consistent control structure in Figure 2.12(b). Here F_A depends on the inventory of A as reflected by the recycle flow D by keeping the reactor feed ratio $(F_A + D)/F_B$ constant at a given value (larger than 1 to make B the limiting reactant). The structure is consistent for all components: C has an outlet in the bottom of the column; B is self-regulated by reaction because it it the limiting reactant, and the feed of A depends on the inventory of A.

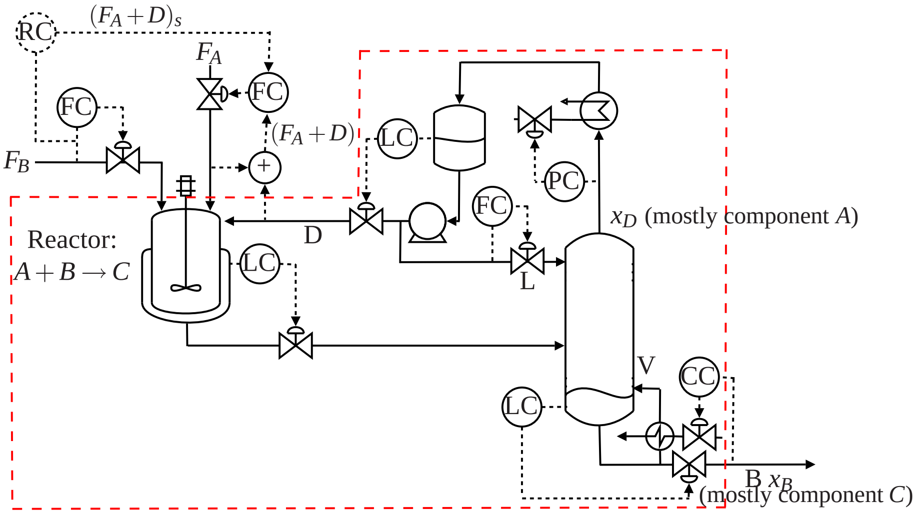
There exist also other consistent inventory control structures, e.g. see Luyben *et al.* (1998, Figure 2.11(b)), but these seem to be more complicated than the one proposed in Figure 2.12(b). For example, one could keep the recycle D constant and use F_A to control the condenser level (main inventory of A), but the dynamics for this “long level” loop are not favorable and this consistent structure is not self-consistent.

2.6 Conclusion

Consistency is a required property since the mass balances must be satisfied for the individual units and the overall plant. An inventory control system can be checked whether it is self-consistent (local “self-regulation” of all inventories) by using the



(a) Inconsistent structure with both reactant flows fixed



(b) Self-consistent structure where feed of reactant A depends on inventory of A (as reflected by D)

Figure 2.12: Reactor-recycle system with two reactants ($A+B$).

self-consistency rule (Rule 2.1). The self-consistency rule follows from the mass balance that must be satisfied for the total mass, component and individual phases.

A direct consequence of the self-consistency rule is the "radiation rule" (Price and Georgakis, 1993), which states that the inventory control structure must be radiating around the location of a fixed flow. Other useful rules that can be developed from the self-consistency rule, is that all system must have at least one given flow (throughput manipulator). Thus, for closed systems, one inventory (preferable the largest) must be left uncontrolled.

Luyben provides the rule to "fix a flow in each recycle". If we interpret the term "fix a flow" to mean "do not use a flow for inventory control", then this rule follows from the requirement of self-consistency provided the recycle loop contains a split that introduced an extra degree of freedom (see Section 2.4.2). If no degree of freedom is introduced by the recycle, as is in the case if we have a separator or flash where the split is (indirectly) fixed by the feed properties, then this rule is not a requirement, e.g. see Figure 2.11(a), where all the flows in the recycle loop are on inventory control.

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