# Emnemodul: Advanced Process Control

**29. Nov. 2018. Time: 0915 – 1200.**

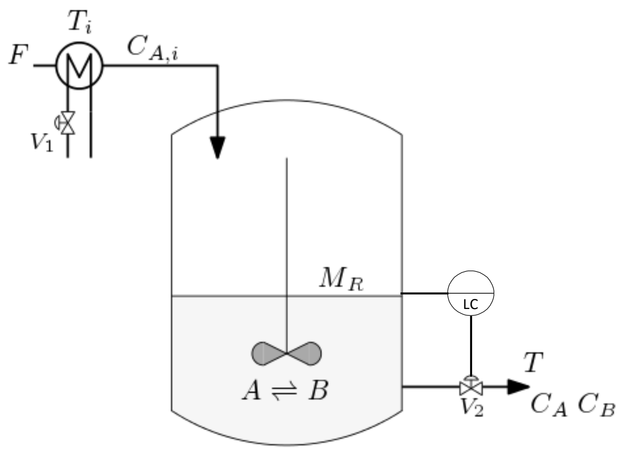
Answer as carefully as possible, preferably using the available space. Answer all questions.
If possible, do not write on the backside of the exam.
You may answer in Norwegian; however, English is preferred.

## Problem 1 – General Questions (15%)

a) State the hierarchical structure often used in process industries.
b) What are the tasks in each layer?
c) In which section of the control hierarchy would you position self-optimizing control?
d) Is it possible to combine SOC with model predictive control (MPC)? Reason your answer!
e) State the top-down and bottom-up approach to control structure design.
f) What does a typical cost function in a chemical process look like?
g) What is meant by "squeeze and shift"? Explain the basic idea and its practical significance.

## Problem 2 – Self–Optimizing Control (20%)

a) Consider the following exothermic CSTR process with a fixed given inflow rate $F$. The concentration of component A in the feed stream $C_{A,i}$ is an unknown disturbance. At nominal conditions $C_{A,i} = 1\ mol\ l^{-1}$.The reactor temperature $T$, concentration of components A and B in the outlet $C_A$ and $C_B$ are available measurements. $M_R$ is the reactor hold-up and $T_i$ is the inlet temperature. The objective is to maximize the profit given by, $J = 2.009\ C_B - (1.657 \times 10^{-3} T_i)^2$, that is, the revenue of the desired product concentration $C_B$ minus a penalty for the heating usage.




For this process shown in the figure above, what would be the ideal self-optimizing variable that would give zero loss when controlled to a constant setpoint? Reason your answer.

b) The nullspace method is one method, which can be used to select a measurement combination $\mathbf{c} = \mathbf{Hy}$ as the self-optimizing variable. For this method, answer the following questions:

1. How many measurements are required for the nullspace method? Can the null space method be used for the system above?
2. The following table shows the *optimal values* for the nominal case ($C_{A,i} = 1\ mol\ l^{-1}$) and for a perturbed case, where the disturbance $C_{A,i} = 1.3\ mol\ l^{-1}$. Using this information, calculate the optimal sensitivity matrix **F**.

| | $\boldsymbol{C_{A,i} = 1}$ | $\boldsymbol{C_{A,i} = 1.3}$ |
|---|---|---|
| $\boldsymbol{C_A\ [mol\ l^{-1}]}$ | 0.498 | 0.644 |
| $\boldsymbol{C_B\ [mol\ l^{-1}]}$ | 0.502 | 0.656 |
| $\boldsymbol{C_T\ [K]}$ | 426.761 | 429.17 |

3. Calculate the measurement combination matrix **H** using the optimal sensitivity matrix **F**.
4. In which situation is the nullspace method optimal, *i.e.* it has zero loss? Derive an expression showing this optimality.

c) The exact local method is a generalization of the nullspace method and a second method to select the self-optimizing variable. What are the advantages of the exact local method compared to the nullspace method?

d) Is it a good idea to control a variable that reaches a maximum or minimum at the optimum? Why?

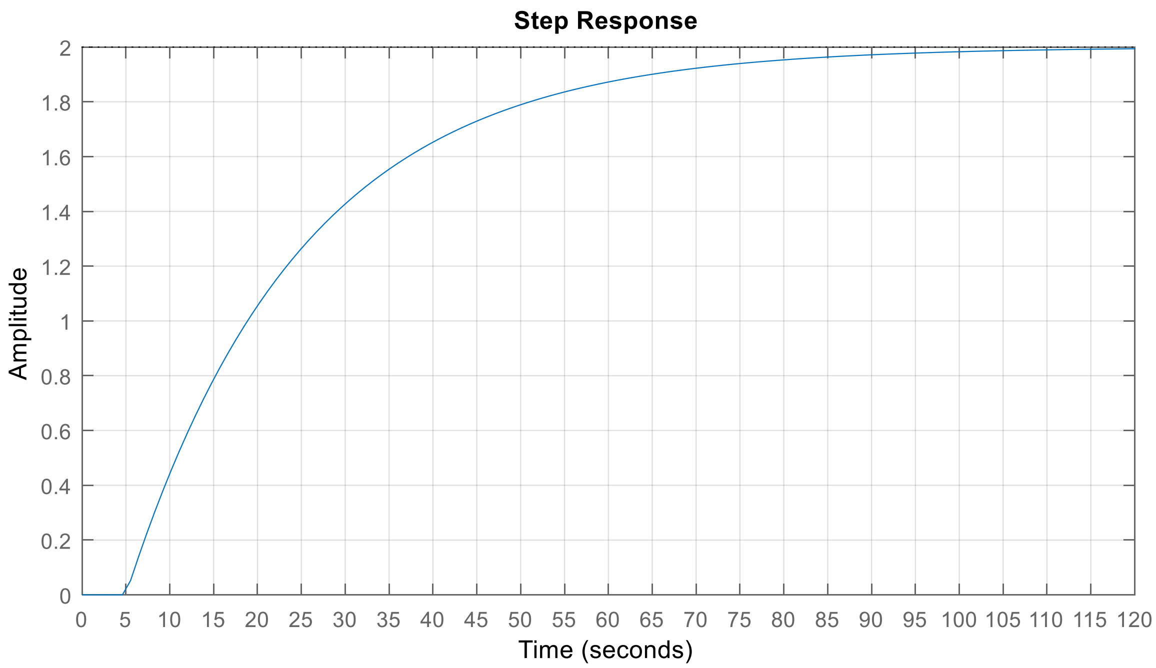
## Problem 3 - PID controller tuning (15%)

a) Consider a process given by the following process model

$$G(s) = \frac{2(1-s)e^{-s}}{(12s+1)(3s+1)(0.2s+1)(0.05s+1)}$$

1. Using the half rule, give a first order plus time delay (FOPTD) approximation of the process.
2. Design a PI controller for this process using the SIMC rules with a desired closed loop time constant $\tau_c = 10$.
3. For the same process model $G(s)$, give a second order plus time delay (SOPTD) approximation of the process using the half-rule.
4. Design a PID controller for this process using the SIMC rules with a desired closed loop time constant $\tau_c = 10$.

b) Consider a different process, for which the step response to a unit step change in the input at time t = 0 is given as shown below.




Assuming perfect measurements (i.e. no additional measurement delay), design a PI controller when $\tau_c = \theta$.

## Problem 4 – Consistency (15%)

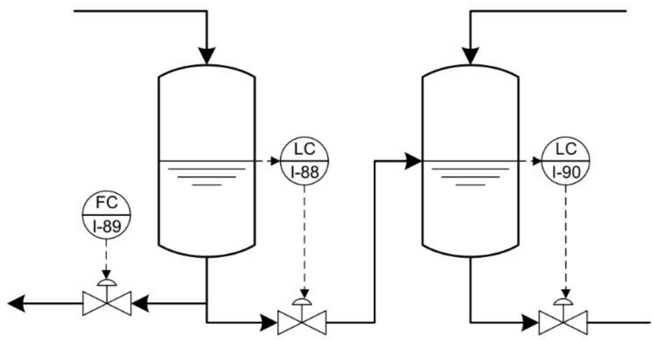
Consistency is a required property for a process in chemical industry. It should be fulfilled in all processes.

a) What do you mean by a consistent control structure? When is a consistent control structure locally consistent?

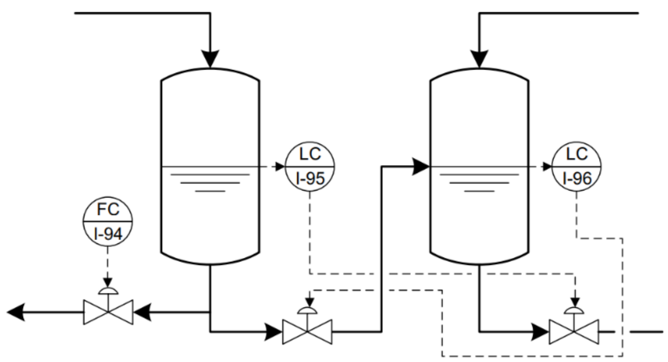
b) What is the "so-called" throughput manipulator (TPM)? Where should one place the throughput manipulator in a system with recycle?

c) Are the following control structure locally and globally consistent and what is (are) the TPM(s)? Justify your answers for global consistency.

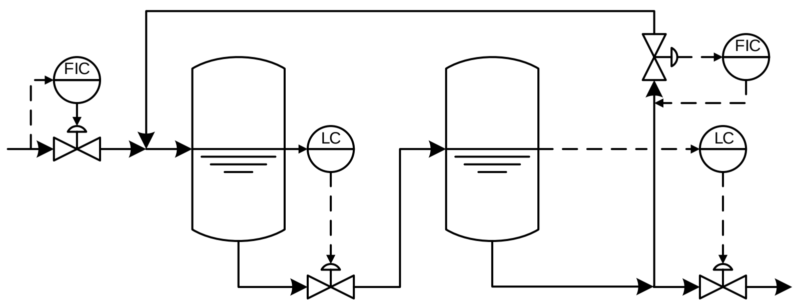
i)



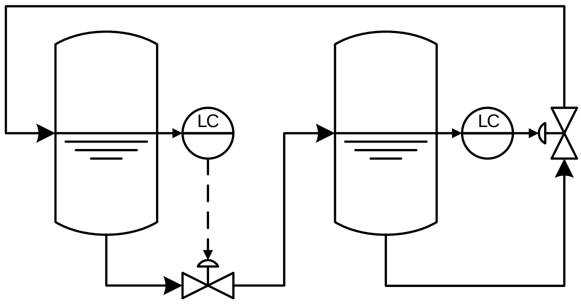

ii)




iii)



iv)

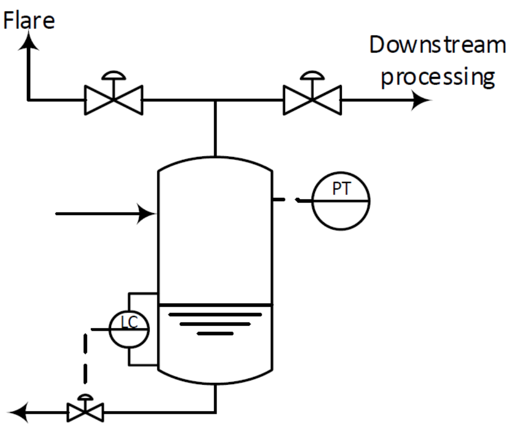


## Problem 5 – Advanced Control Structures (15%)

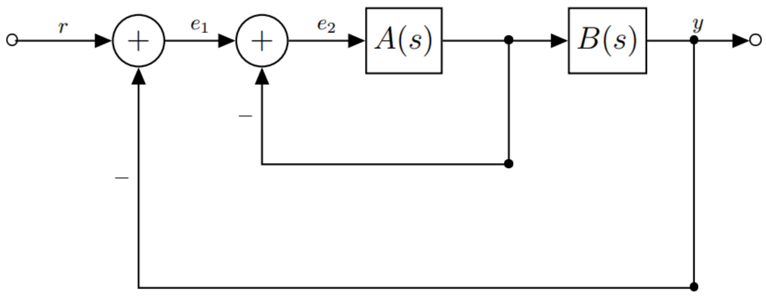
In the process shown below, we need tight control of the pressure in the vessel. Under normal operation, the gas is routed to further downstream processing. For safety reasons, the vessel is also equipped with a flare line, where under extreme conditions, excess gas must be flared to the atmosphere if the pressure in the vessel becomes too high.

a) Since you have 2 MVs and 1CV, propose a control structure to achieve this objective and explain how the proposed control structure achieves this.

Note: Assume that the level in the tank is tightly controlled using the level controller as shown in the figure below. The pressure measurement is also shown in the figure below.




b) The figure below shows the block diagram of a cascade controller:




1. Derive the transfer function $T(s)$ from $r \rightarrow y$.

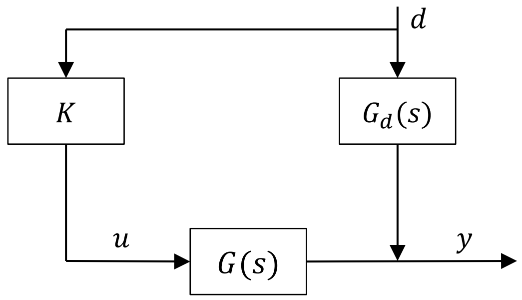
2. Name two properties that represent a good candidate CV for the inner loop in a cascade controller.

c) The relative gain array (RGA) is a tool one can use to decide on controller pairing in multivariable systems. Additionally, it gives you information about the influence on coupling. Consider the following steady state RGA for a process with 3 inputs $u_1$, $u_2$ and $u_3$ and 3 controlled variables $y_1$, $y_2$ and $y_3$:

$$RGA = \begin{bmatrix} -0.08 & 1.18 & -0.10 \\ -0.33 & -0.46 & 1.79 \\ 1.41 & 0.28 & -0.69 \end{bmatrix}$$

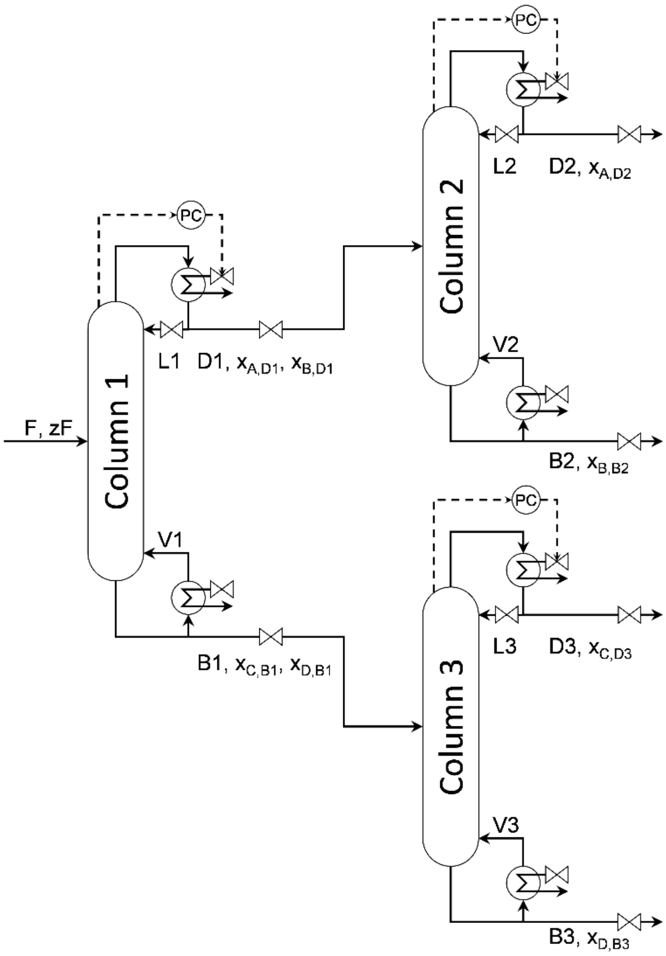
How would you pair the inputs with the controlled variables?

d) Consider a process $G(s)$, which is subjected to disturbance given by $G_d(s)$, as shown in the block diagram below. If you want to design a feedforward controller to reject effect of dis-trubances for this system, what would be the ideal feedforward controller $K$ (assuming that it is realizable)?



## Problem 7 (20%)

Consider a sequence of distillation columns for separating four components A, B, C, and D as shown in the figure below.




The feed and its composition are given by the upstream processes and our outside of the analysis. The pressure in each column is controlled by the coolant flowrate (see figure).

Purity constraints are imposed on the four products (distillate and bottom streams of column 2 and 3) as follows

$x_{A,D2} \geq 97\%$ A
$x_{B,B2} \geq 97\%$ B
$x_{C,D3} \geq 97\%$ C
$x_{C,B3} \geq 97\%$ D

To prevent flooding of the columns, the maximum vapor flowrate in the stripping sections of the columns are given by:

$V_1 \leq 5$ mol/s
$V_2 \leq 3$ mol/s
$V_3 \leq 4$ mol/s

Your task is the minimization of the costs given by

$$J = -\text{Profit} = p_F F + p_V\left(V_1 + V_2 + V_3\right) - p_{D2}D_2 - p_{B2}B_2 - p_{D3}D_3 - p_{B3}B_3$$

In which the product prices are given by

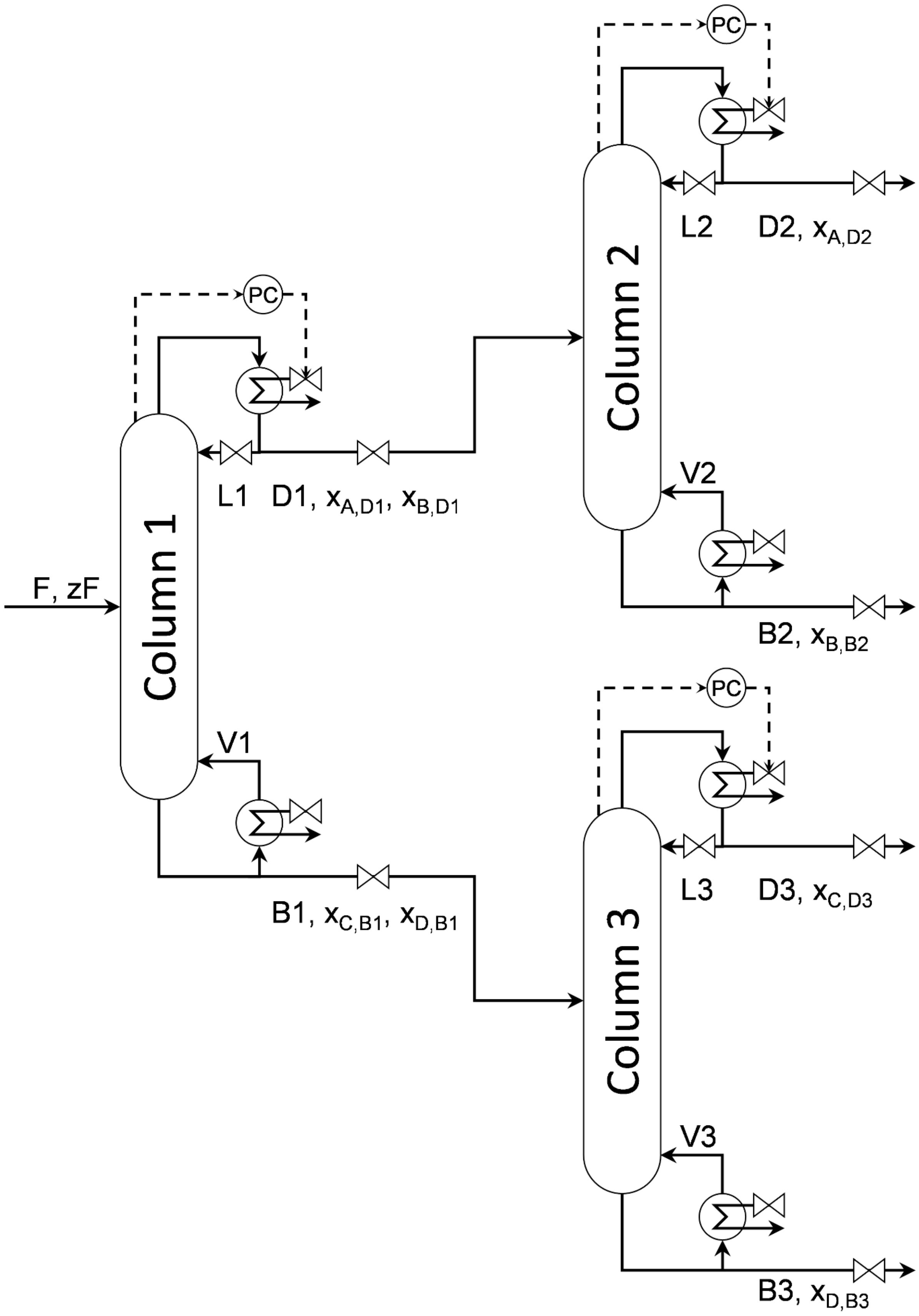
$p_A = 5$ \$/mol
$p_B = 1$ \$/mol
$p_C = 5$ \$/mol
$p_D = 1$ \$/mol

As the process is operated in Iceland with cheap industrial energy prices, the energy price is compared to the general industrial energy price very low and given by:

$p_V = 0.0001$ \$/mol

Based on the above information, answer the following questions.

a) How many dynamic and steady-state degree of freedoms does this system have?
b) Based on your experience and engineering know-how, which constraints will be active for the above mentioned system. Justify your answer.
c) Propose a control structure for this case and draw it in the figure on the next page. Explain your choice.
d) If you have degree of freedoms remaining that are not used for controlling active constraints or stabilizing inventories, then propose possibilities on how to use them.
e) What happens, if the feed rate is increased? Would you suggest moving the TPM?
f) The product streams of A and C shall be sold directly to the customers, hence the product composition constraints are hard constraint and may not be violated at any point. Can the idea of squeeze and shift be used? How would you apply it?


PC
PC
PC
L2
D2, $x_{A,D2}$
Column 2
V2
B2, $x_{B,B2}$
L1
D1, $x_{A,D1}$, $x_{B,D1}$
F, zF
Column 1
V1
B1, $x_{C,B1}$, $x_{D,B1}$
L3
D3, $x_{C,D3}$
Column 3
V3
B3, $x_{D,B3}$