CT561: Systems Modelling & Simulation

Lecture 10: Higher Order Models

Chapter 4, J. Duggan (2016)

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https://github.com/JimDuggan/SDMR

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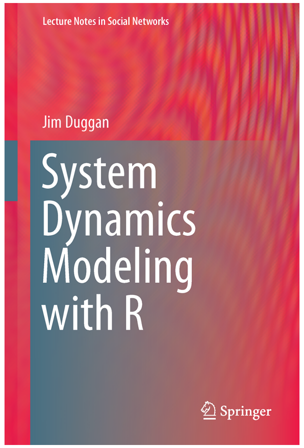
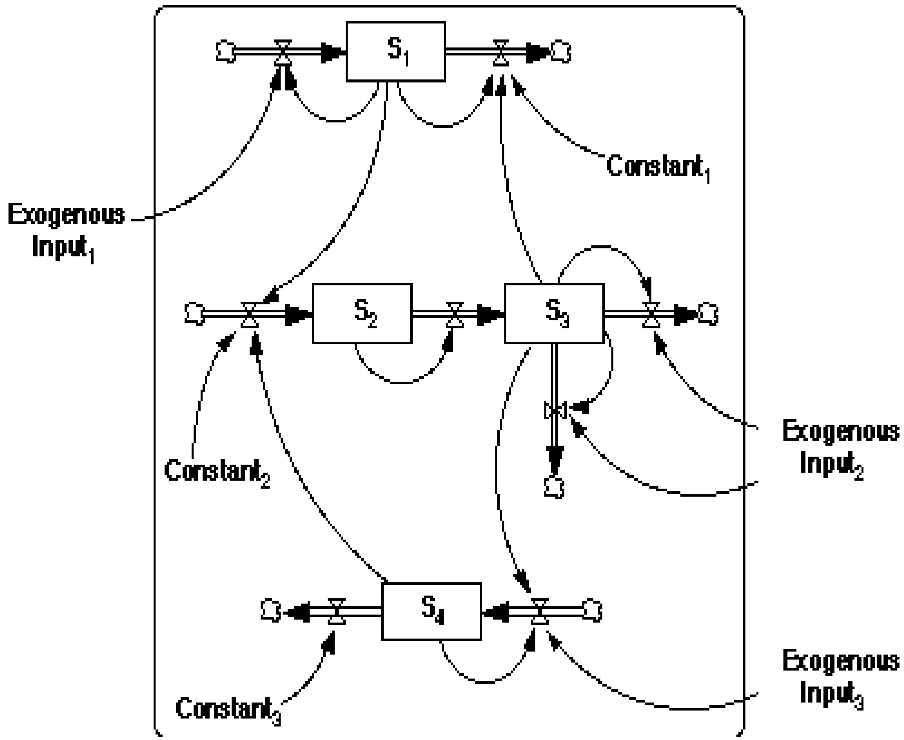


Higher Order Models

Important situations in management, economics, medicine and social behavior often lose reality if simplified to less than fifth-order nonlinear dynamic systems.

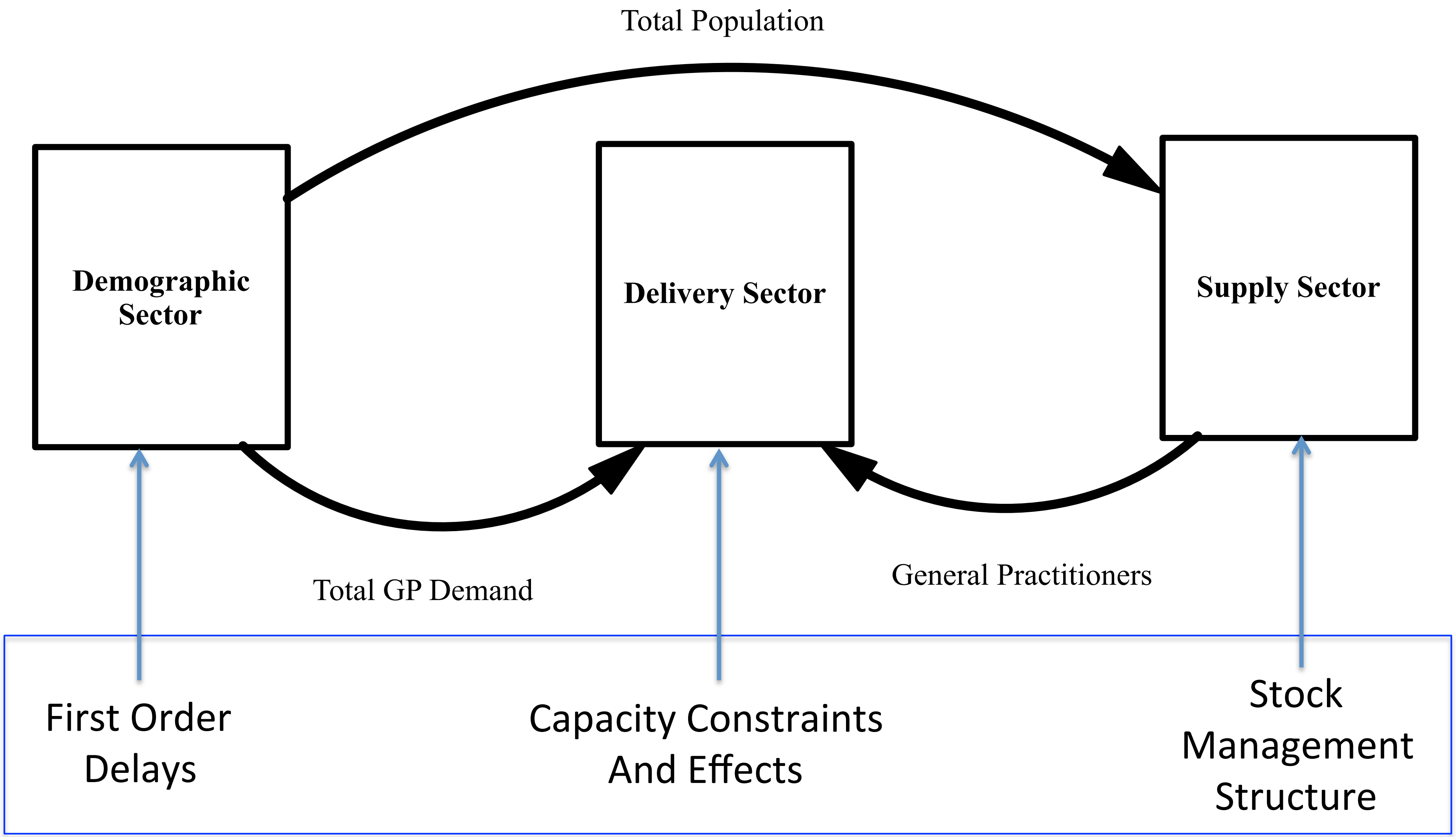
Often the model representation must be twentieth-order or higher. (Forrester 1987).



Example: A Health Care Model

- A ***demographic*** sector, which is an aging chain that captures the dynamics of population change, across a number of age cohorts.
- A ***delivery*** sector, which is a demand-capacity model that captures how the primary care system responds to demand.
- A ***supply*** sector, which contains a stock management structure that regulates the supply of general practitioners, based on a ratio of the overall population.

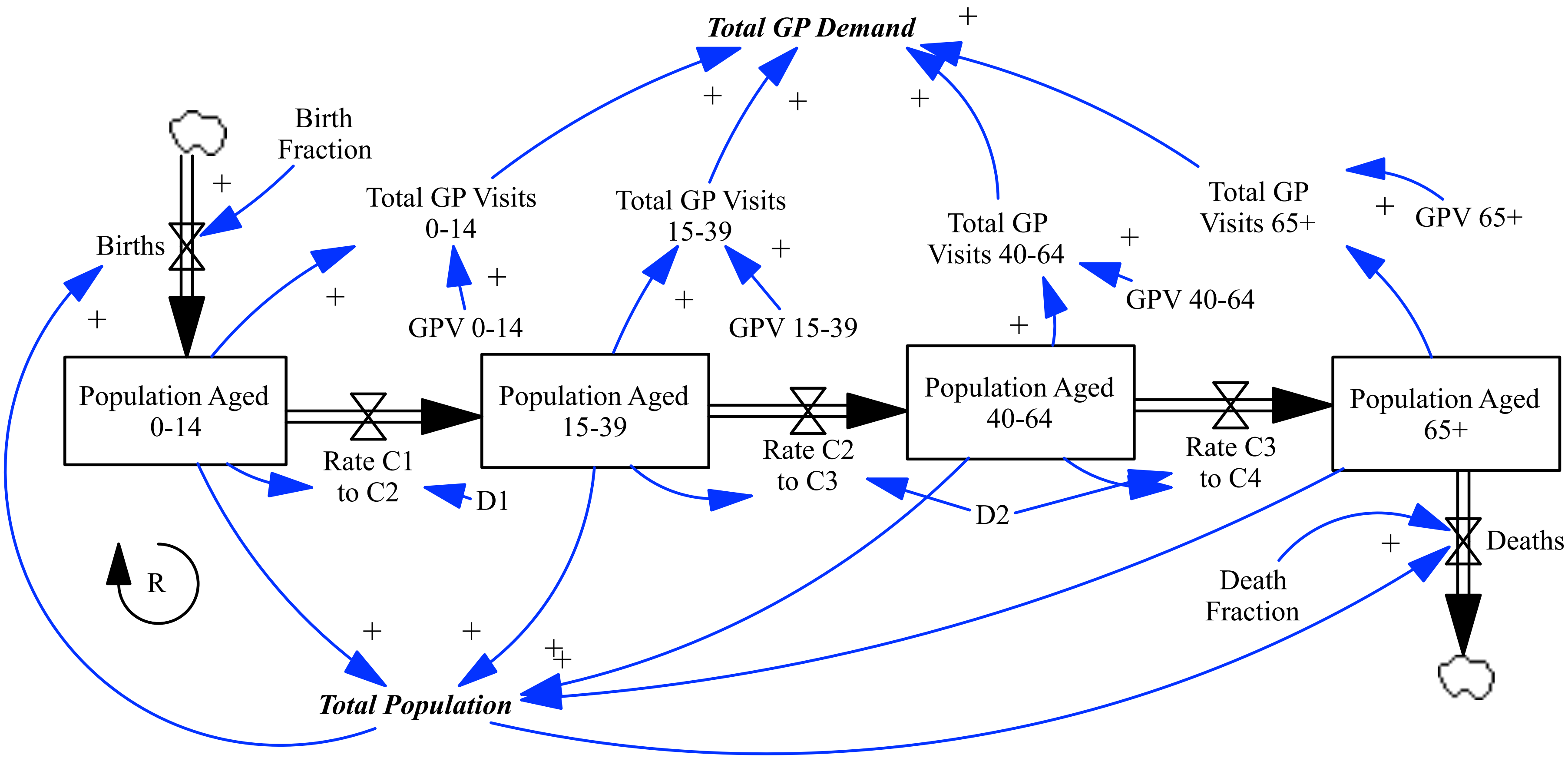
A modular approach (Sectors)

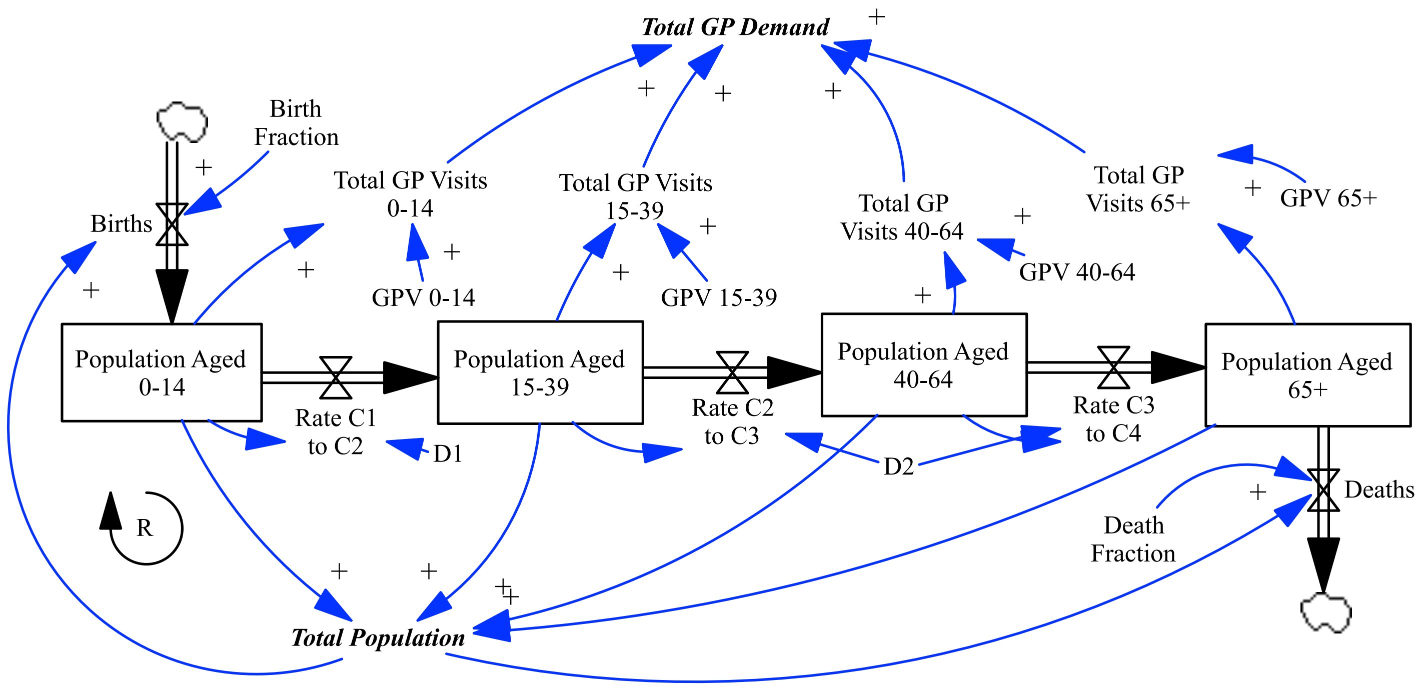


The Demographic Sector

- An *aging chain* structure simulates population maturation, as well as births and deaths.
- The number of cohorts is simplified to four, and no distinction is made between male and female. Also, there is no immigration or emigration in the model, and all the removals are from the oldest cohort.
- First order delays are used to model cohort progression, where the average delay time is 15 years for the first cohort, and 25 years for the other cohorts.
- Births are based on a fixed proportion of the total population.
- The birth and death rates are exogenous, which is a limitation of this initial model.

Stock and Flow Model





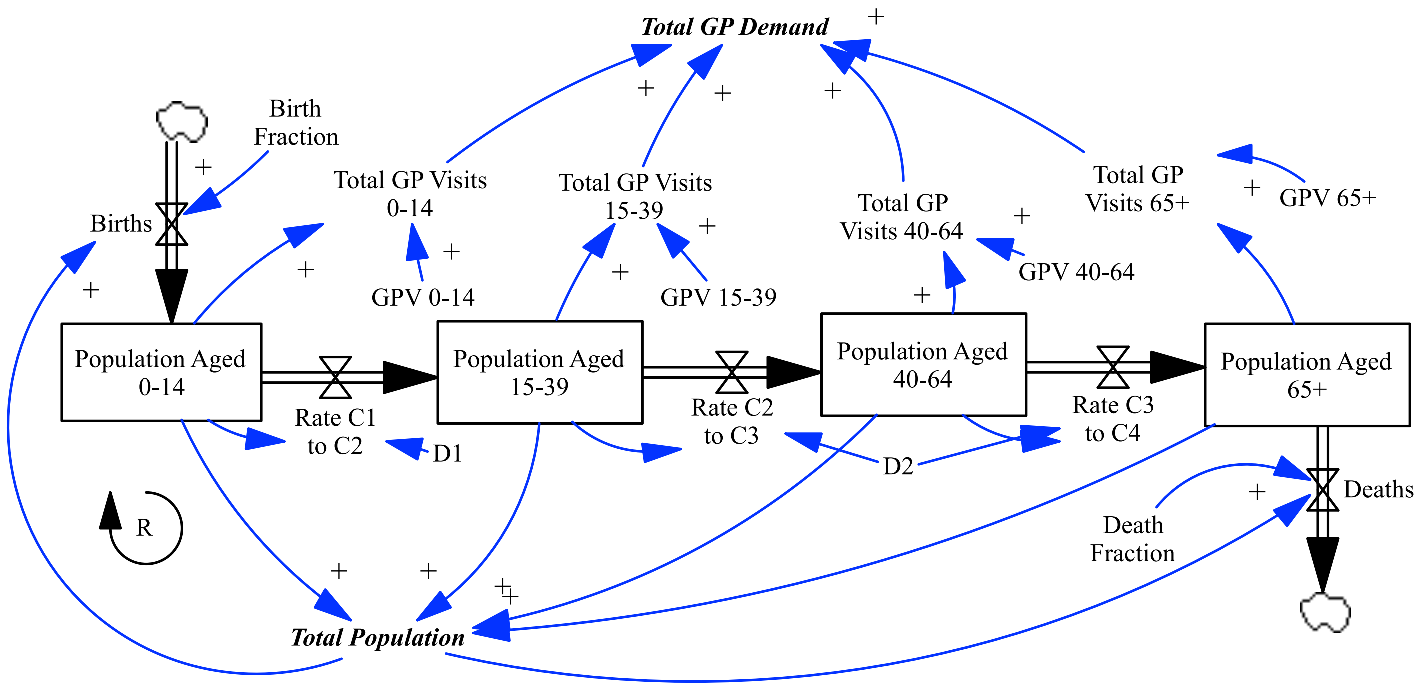
$$P_{0-14} = INTEGRAL(Births - Rate\ C_1 to\ C_2, 1.0M) \tag{4-25}$$

$$P_{15-39} = INTEGRAL(Rate\ C_1 to\ C_2 - \ Rate\ C_2 to\ C_3, 1.5M) \tag{4-26}$$

$$P_{40-64} = INTEGRAL(Rate\ C_2 to\ C_3 - \ Rate\ C_3 to\ C_4, 2.0M) \tag{4-27}$$

$$P_{65+} = INTEGRAL(Rate\ C_3 to\ C_4 - \ Deaths, 0.5M) \tag{4-28}$$

$$Total\ Population = \ P_{0-14} + \ P_{15-39} + \ P_{40-64} + \ P_{65+} \tag{4-29}$$



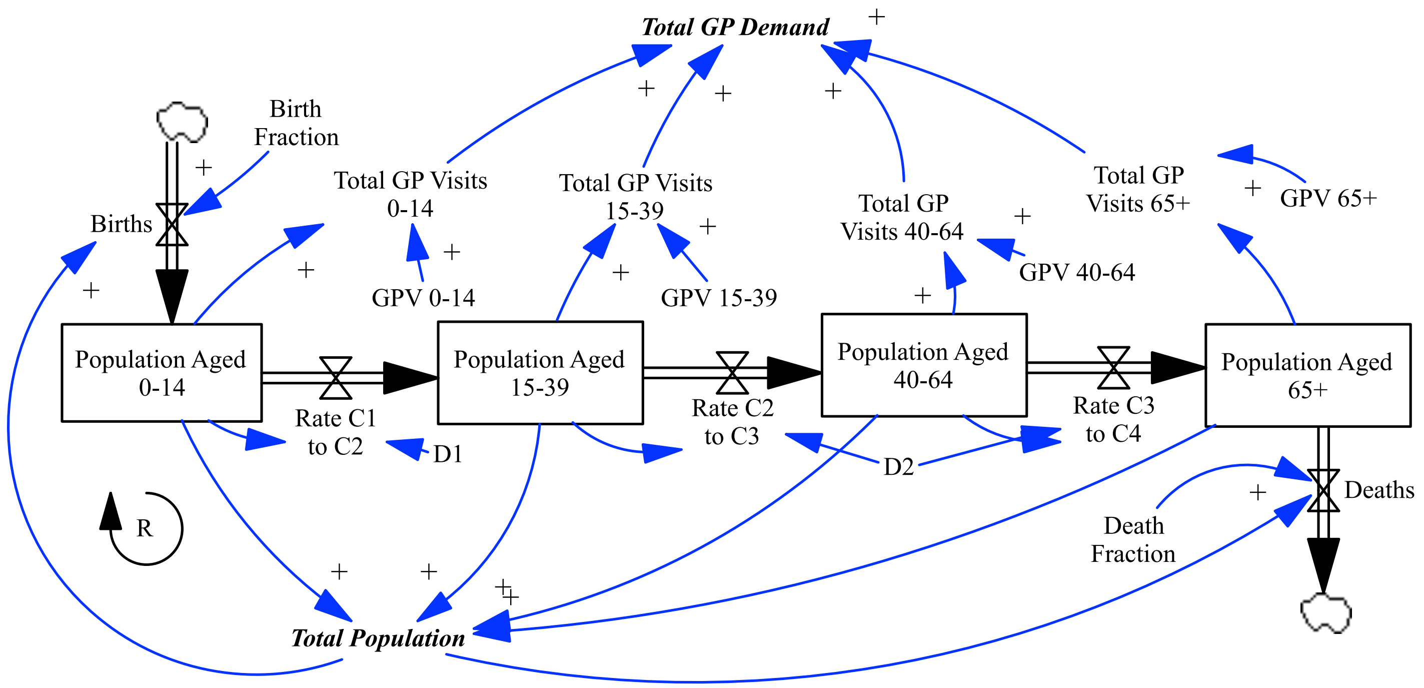
$$Births = Total\ Population \times Birth\ Fraction \tag{4-30}$$

$$Rate\ C_1 to\ C_2 = P_{0-14} \ /\ D_1 \tag{4-31}$$

$$Rate\ C_2 to\ C_3 = P_{15-39} \ /\ D_2 \tag{4-32}$$

$$Rate\ C_3 to\ C_4 = P_{40-64} \ /\ D_2 \tag{4-33}$$

$$Deaths = Total\ Population \times Death\ Fraction \tag{4-34}$$

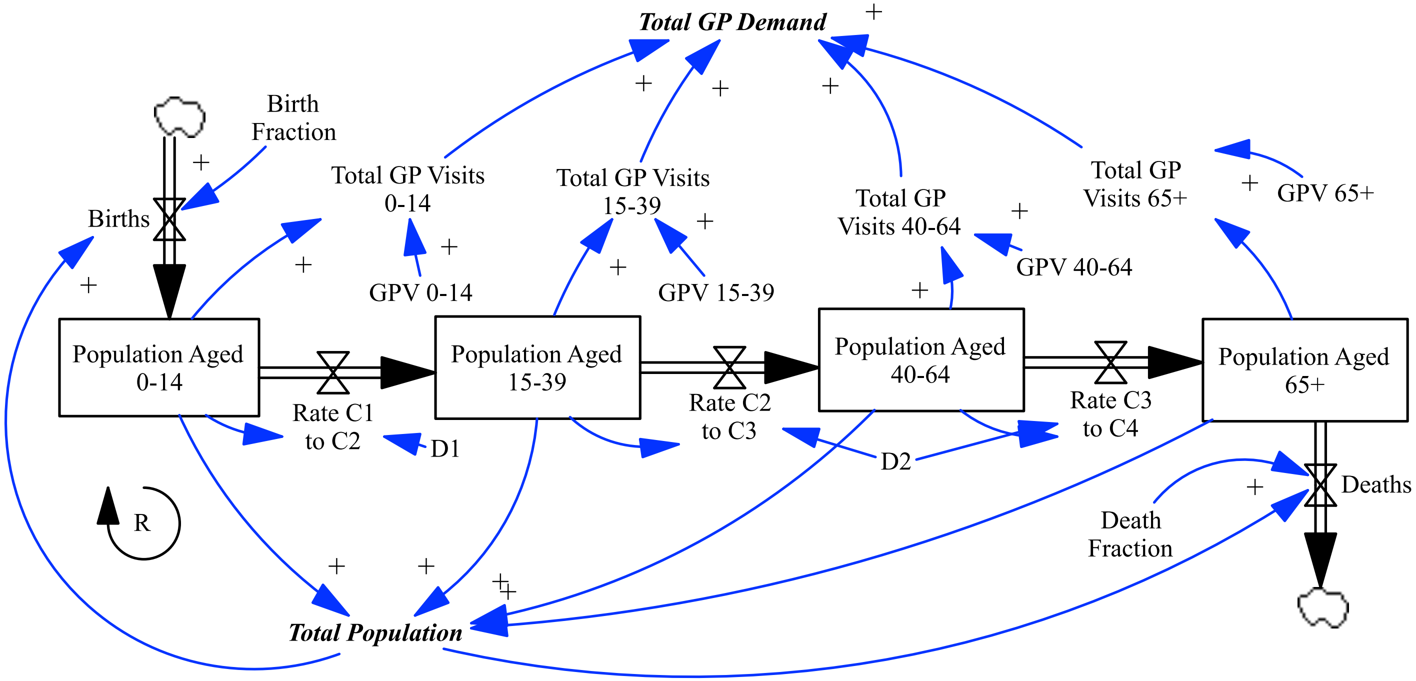


$$Birth\ Fraction = 20\ /\ 1000 \tag{4-35}$$

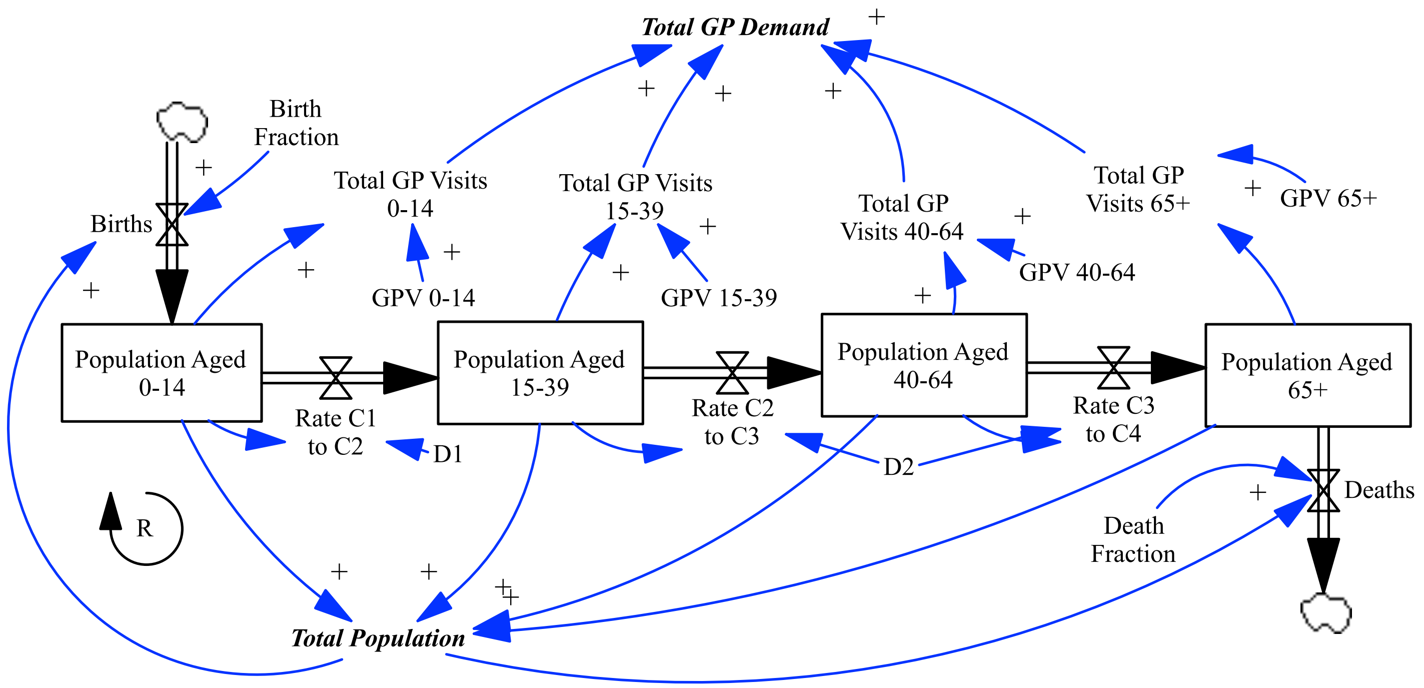
$$Death\ Fraction = 7\ /\ 1000 \tag{4-36}$$

$$D_1 = 15 \tag{4-37}$$

$$D_2 = 25 \tag{4-38}$$



$$GPV_{0-14} = 3 \tag{4-39}$$
$$GPV_{15-39} = 4 \tag{4-40}$$
$$GPV_{40-14} = 5 \tag{4-41}$$
$$GPV_{65+} = 10 \tag{4-42}$$



$$TGPV_{0-14} = P_{0-14} \times GPV_{0-14} \tag{4-43}$$

$$TGPV_{15-39} = P_{15-39} \times GPV_{15-39} \tag{4-44}$$

$$TGPV_{40-64} = P_{40-64} \times GPV_{40-64} \tag{4-45}$$

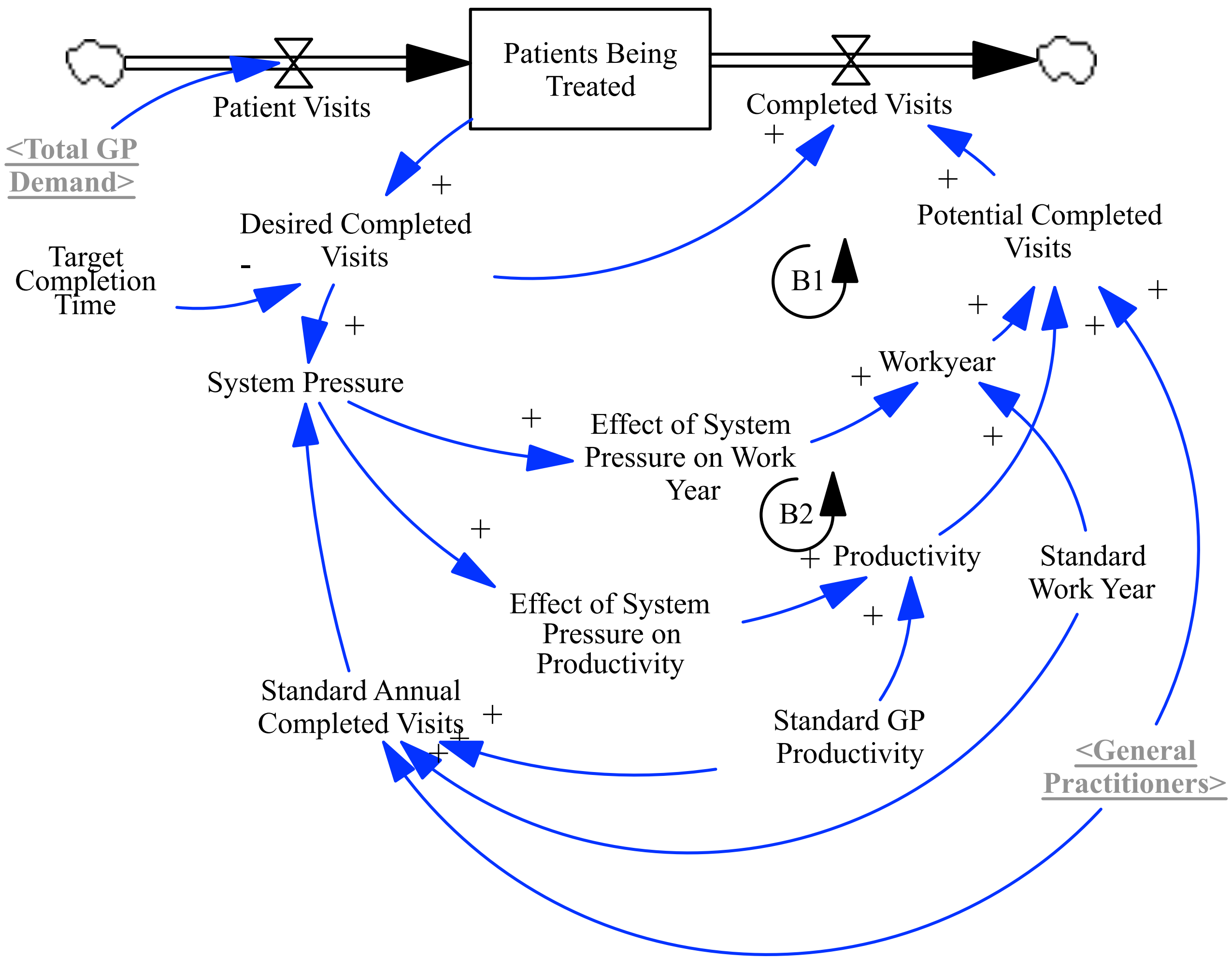
$$TGPV_{65+} = P_{65+} \times GPV_{65+} \tag{4-46}$$

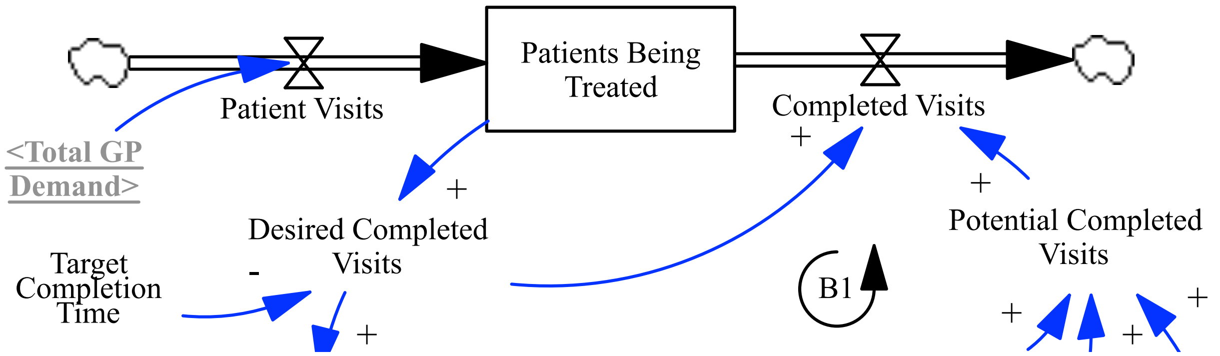
$$Total\ GP\ Demand = TGPV_{0-14} + TGPV_{15-39} + TGPV_{40-64} + TGPV_{65+} \tag{4-47}$$

The Delivery Sector

- The delivery sector is informed by the service capacity model described by Oliva (1996, 2001), and Sterman (2000).
- It provides a convenient structure to model a resource-constrained system.
- The model contains variables that model capacity, which include the length of the work year, the average daily productivity of GPs, and the number of available general practitioners.
- Contains system responses to deal with increasing pressure

Delivery Sector



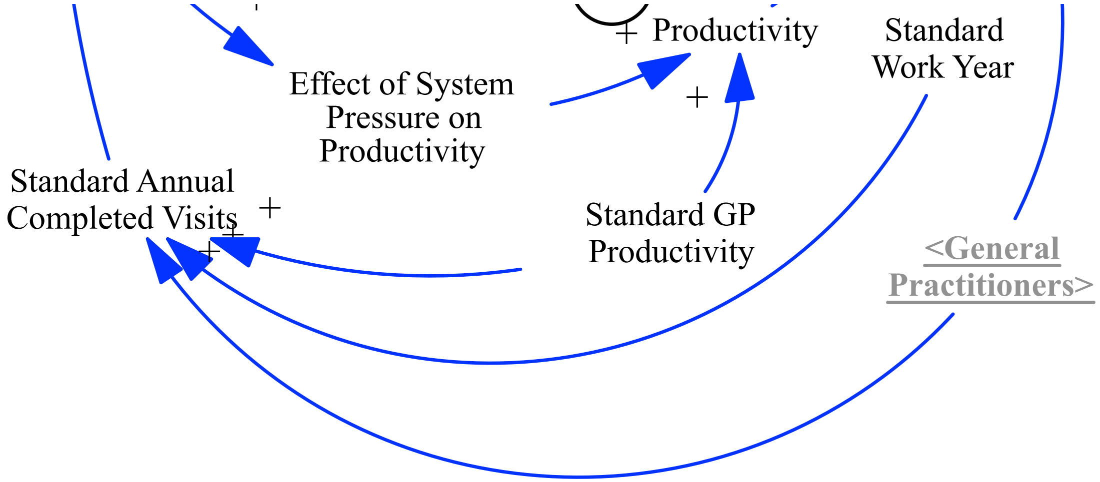


$$PBT = INTEGRAL(Patient\ Visits - Completed\ Vists, 24M) \quad (4\text{-}48)$$

$$Patient\ Visits = Total\ GP\ Demand \quad (4\text{-}49)$$

$$Desired\ Completed\ Visits = PBT\ /\ Target\ Completion\ Time \quad (4\text{-}50)$$

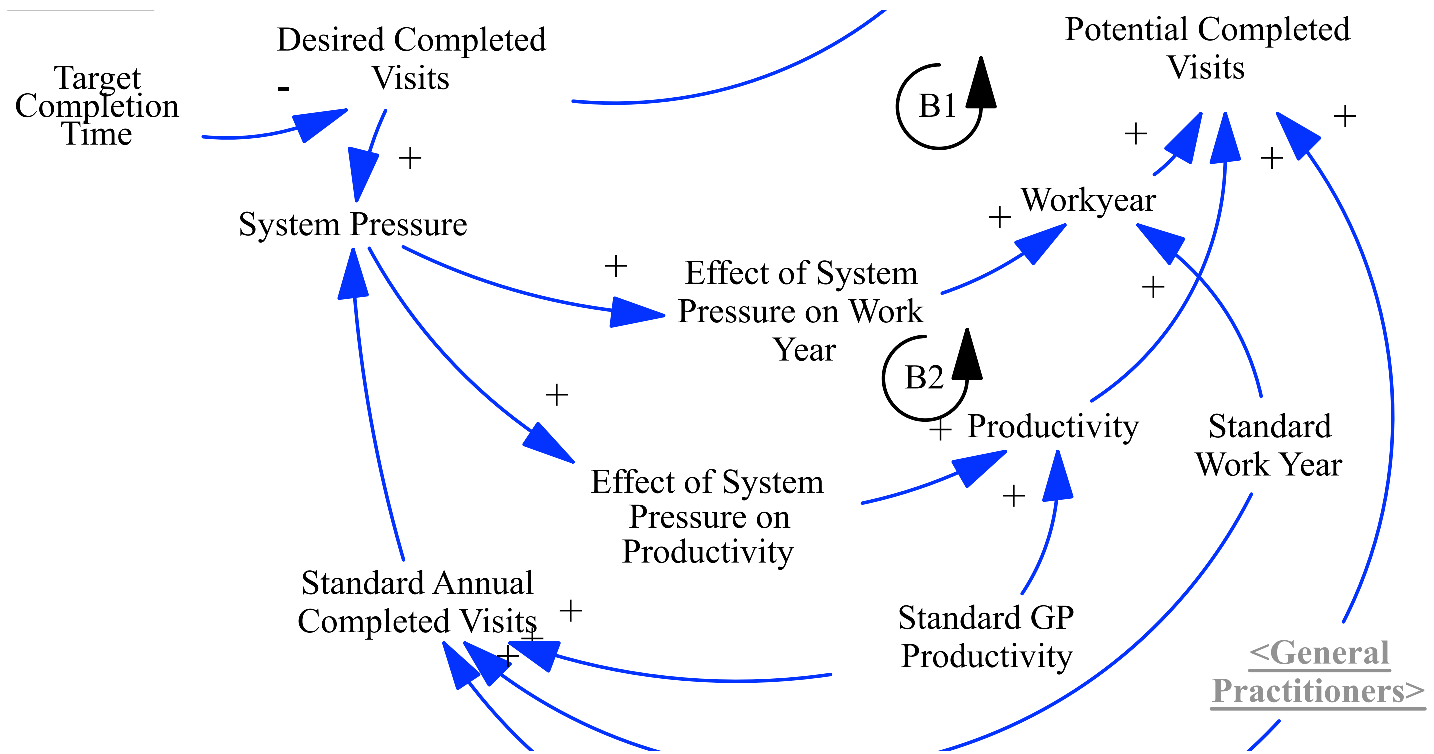
$$Target\ Completion\ Time = 1 \quad (4\text{-}51)$$



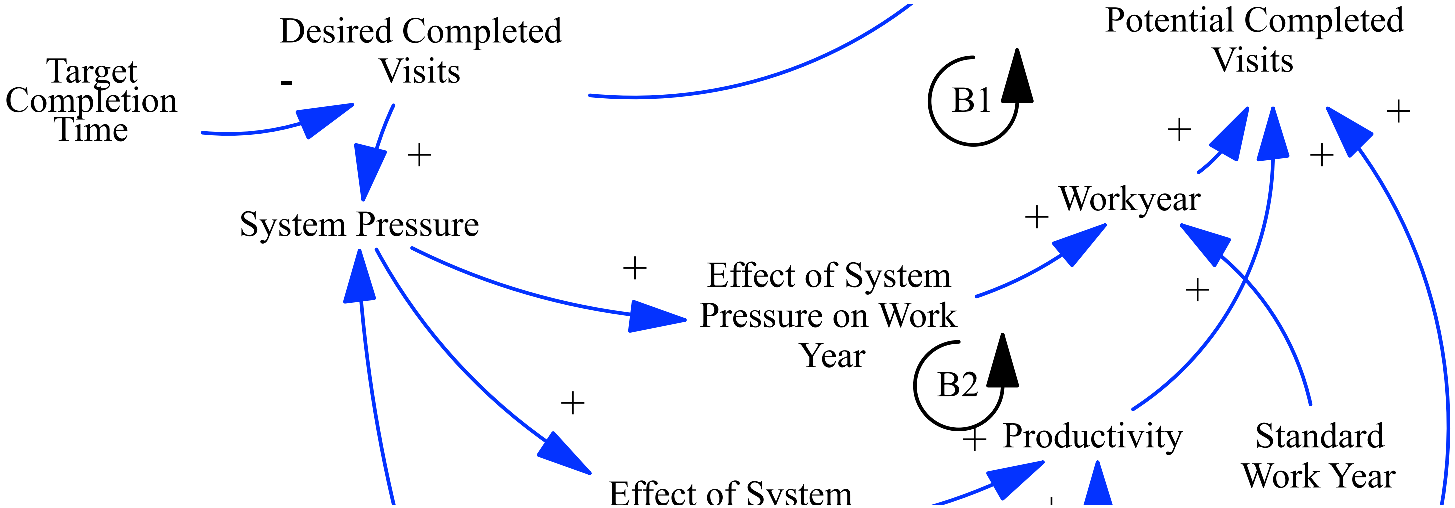
$$\begin{aligned}&\textit{Standard Annual Completed Visits} \\ &\quad = \textit{General Practitioners} \times \textit{Standard Workyear} \\ &\quad \times \textit{Standard GP Productivity}\end{aligned} \tag{4-52}$$

$$\textit{Standard Workyear} = 250 \tag{4-53}$$

$$\textit{Standard GP Productivity} = 24 \tag{4-54}$$



$$System\ Pressure\ = Desired\ Completed\ Visits\ / Standard\ Annual\ Competed\ Visits \qquad (4\text{-}55)$$

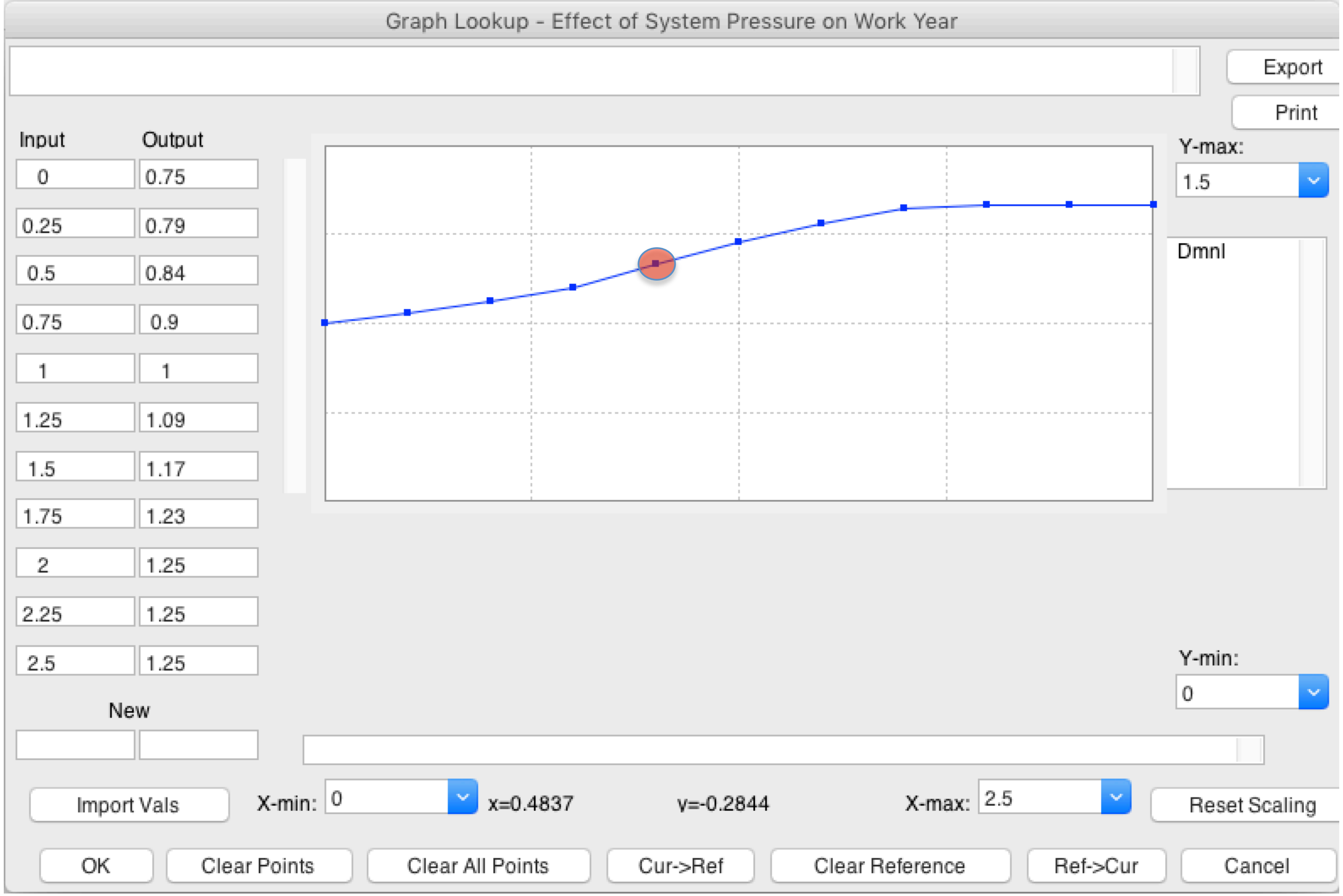


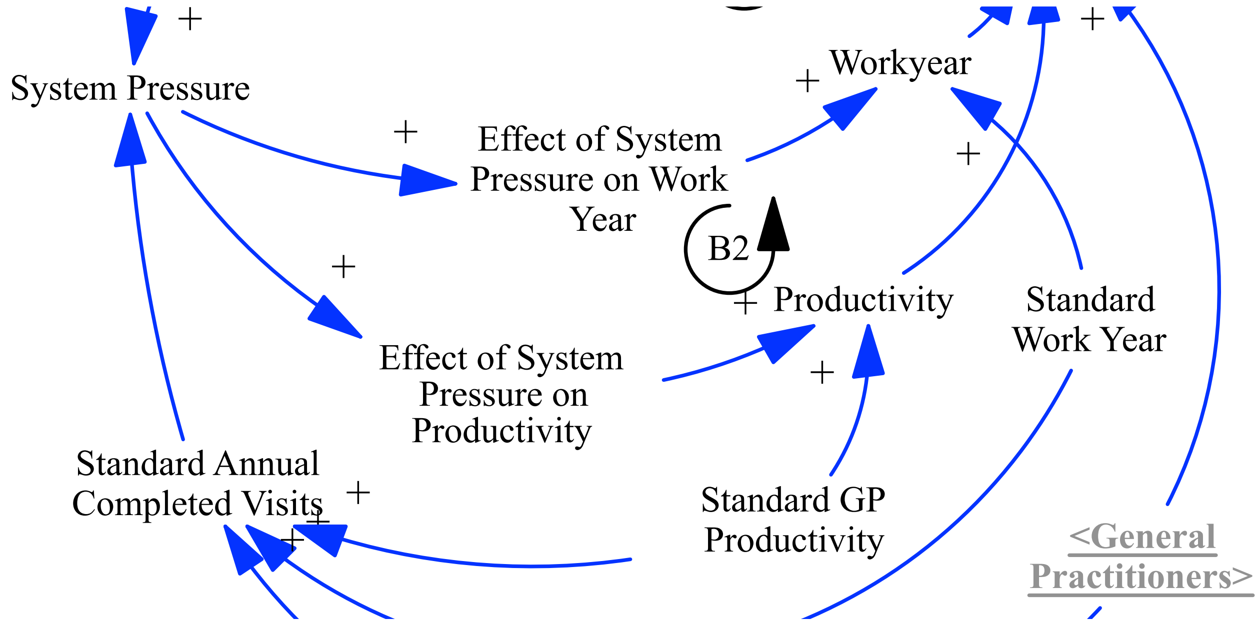
$$Effect\ of\ System\ Pressure\ on\ Work\ Year = GRAPH(System\ Pressure) \tag{4-56}$$

$$(0.0,0.75), (0.25,0.79), (0.5,0.84), (0.75,0.90), (1.0,1.0), (1.25,1.09), (1.5,1.17),$$
$$(1.75,1.23), (2.0,1.25), (2.25,1.25), (2.5,1.25)$$

$$Workyear = Effect\ of\ System\ Pressure\ on\ Workyear \times Standard\ Workyear \tag{4-57}$$

Effect of System Pressure on Work Year



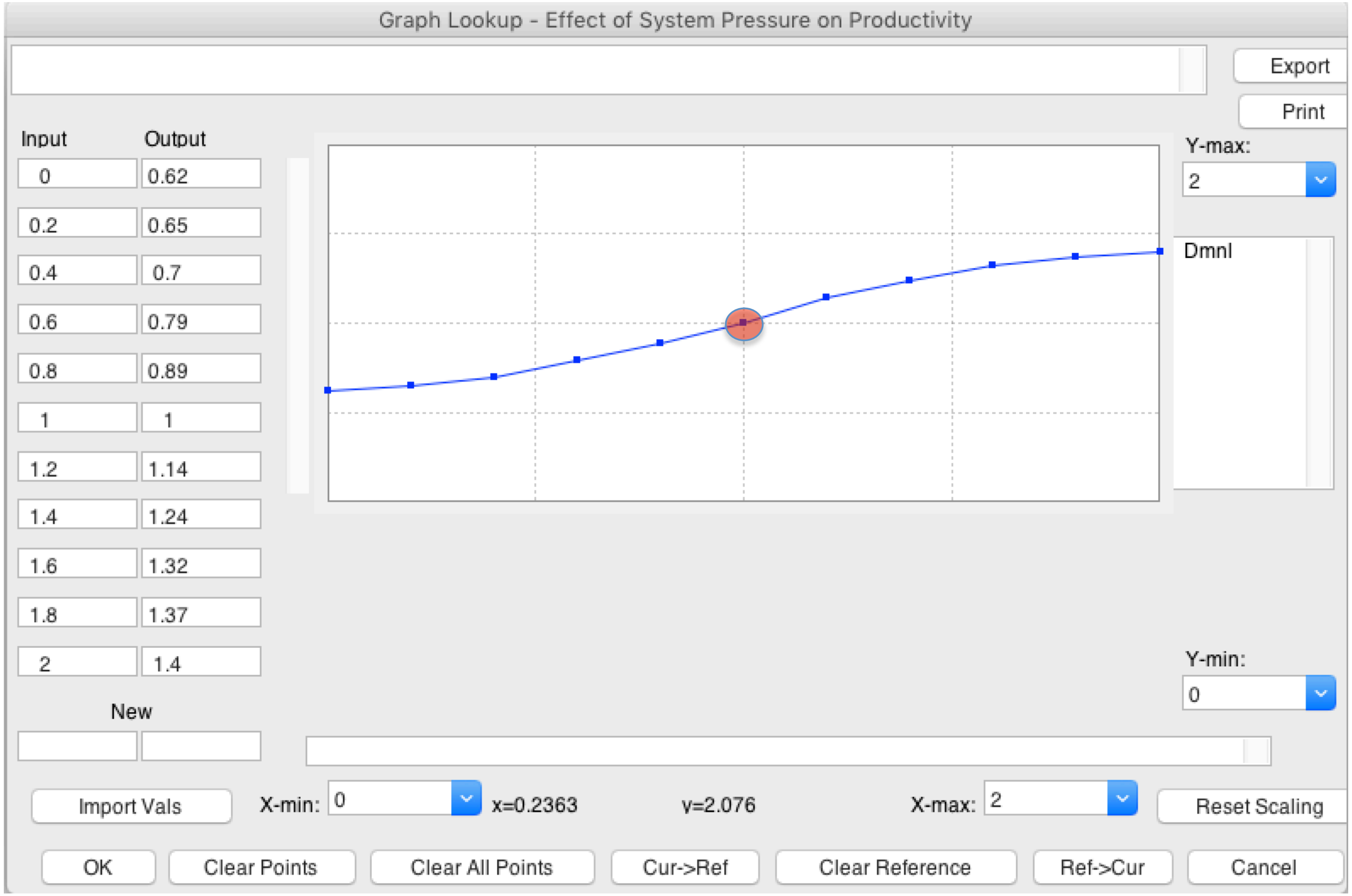


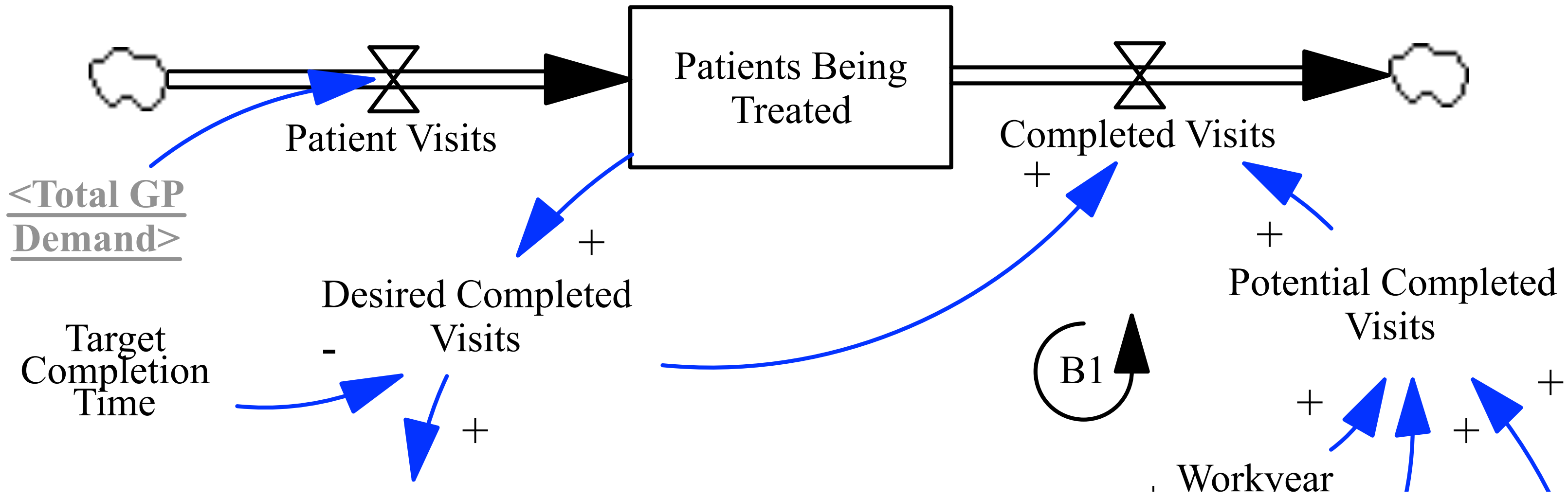
$$Effect\ of\ System\ Pressure\ on\ Productivity = GRAPH(System\ Pressure) \tag{4-58}$$

(0.0,0.62), (0.2,0.65), (0.4,0.84), (0.6,0.79), (0.8,0.89), (1.0,1.0), (1.2,1.14), (1.4,1.24), (1.6,1.32), (1.8,1.37), (2.0,1.4)

$$Productivity = Effect\ of\ System\ Pressure\ on\ Productivity \times Standard\ GP\ Productivity \tag{4-59}$$

Effect of System Pressure on Productivity





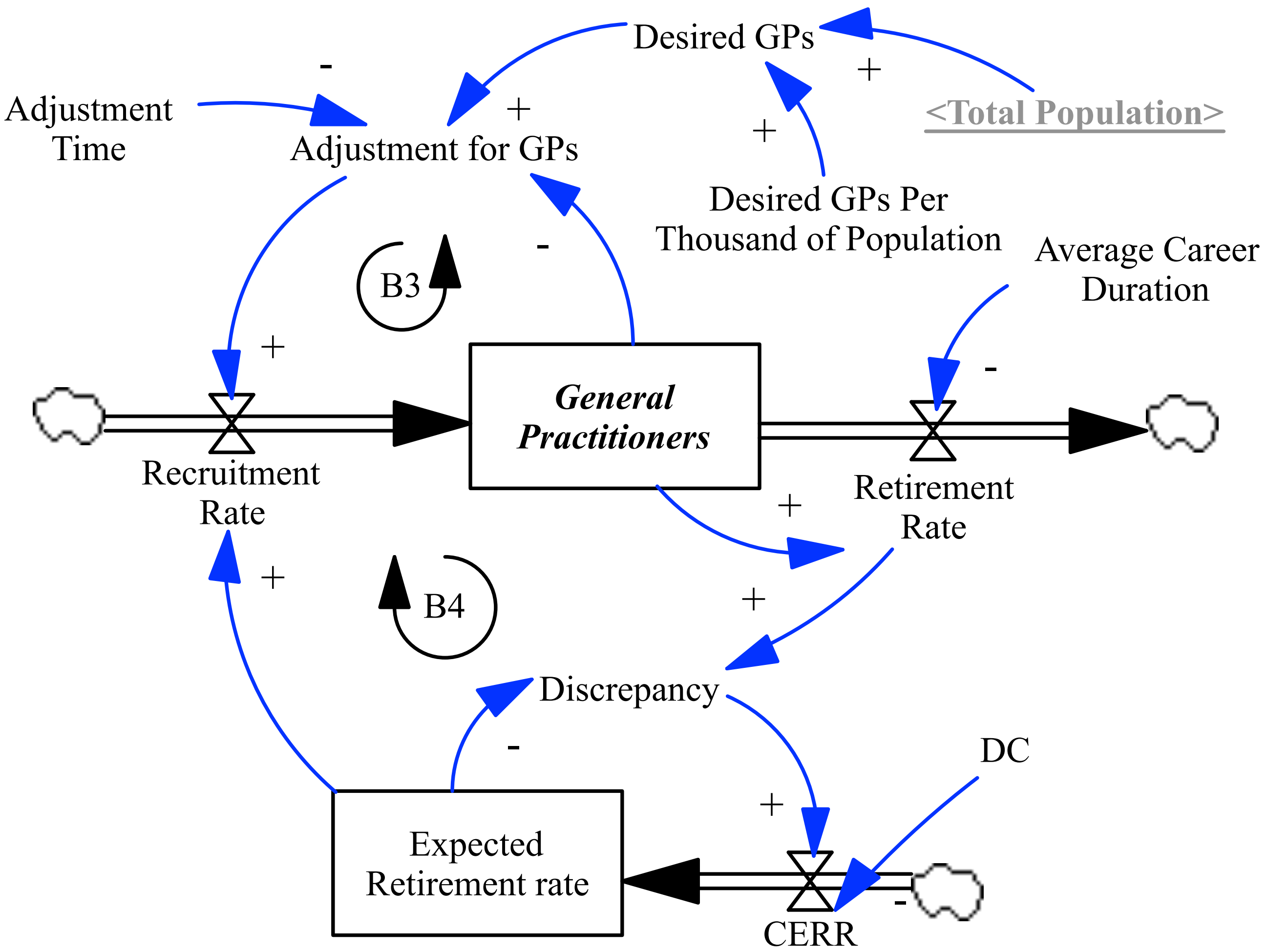
$$\textit{Potential Completed Visits} = \textit{General Practitioners} \times \textit{Productivity} \times \textit{Workyear} \qquad (4\text{-}60)$$

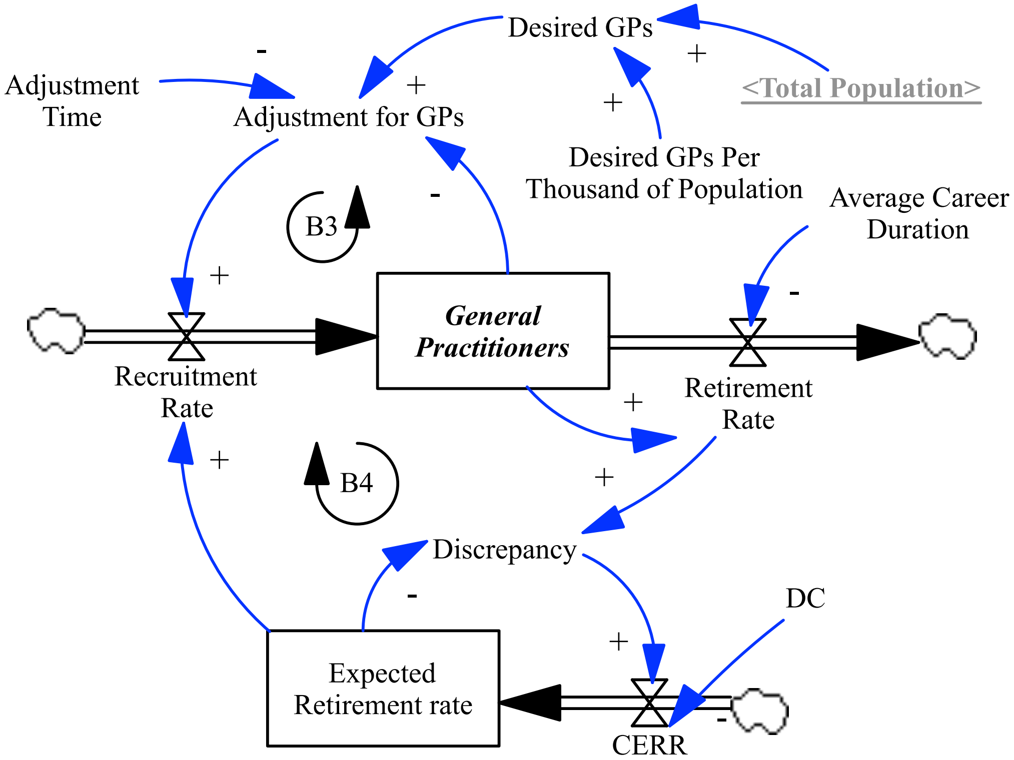
$$\textit{Completed Visits} = MIN(\textit{Desired Completed Visits}, \textit{Potential Completed Visits}) \qquad (4\text{-}61)$$

The Supply Sector

- The supply sector models the GP resource base in terms of recruitment into the profession, and retirement after many years of service.
- Based on the ***Stock Management Structure***
- It assumes there is a ready supply of qualified personnel ready to enter practice.
- The estimation for the desired number of GPs is a crude measure, based on a fraction of the overall population. This will ensure that the number of GPs grow as the population grows.
- There is no distinction between the different stages in a GP professional's career. These changes, if made, could impact on the available work year, and also influence overall productivity.

Supply Sector

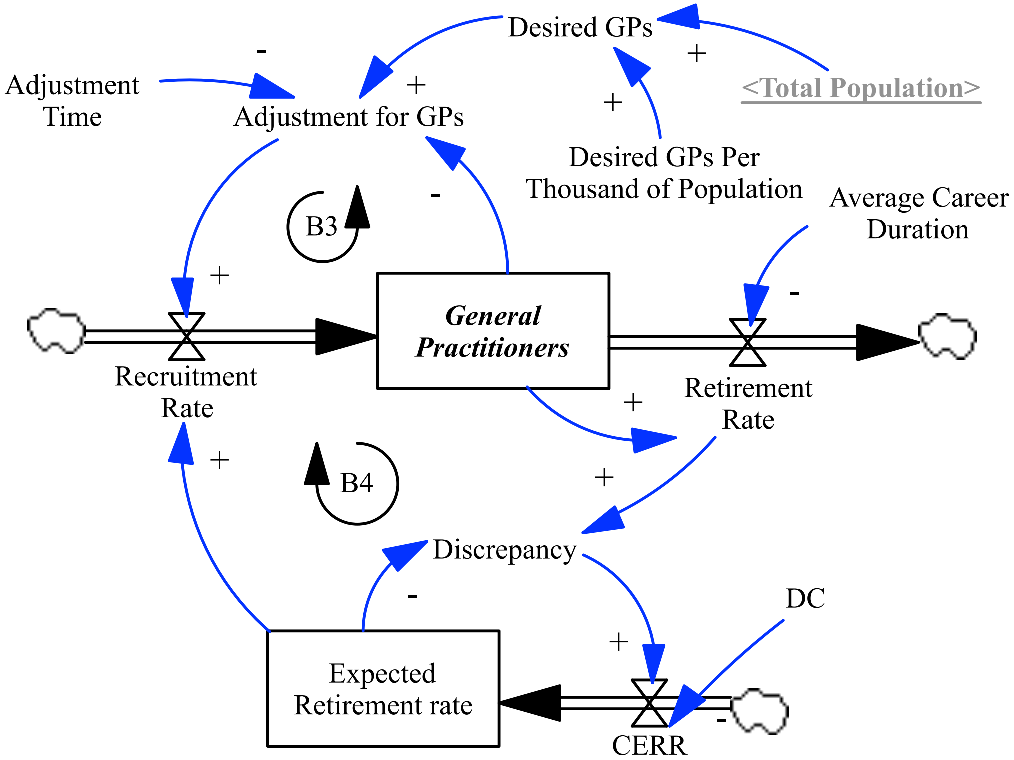




$$\text{General Practitioners} = \text{INTEGRAL}(\text{Recruitment Rate} - \text{Retirement Rate}, 4000) \tag{4-62}$$

$$\text{Retirement Rate} = \text{General Practitioners}/\text{Average Career Duration} \tag{4-63}$$

$$\text{Average Career Duration} = 40 \tag{4-64}$$

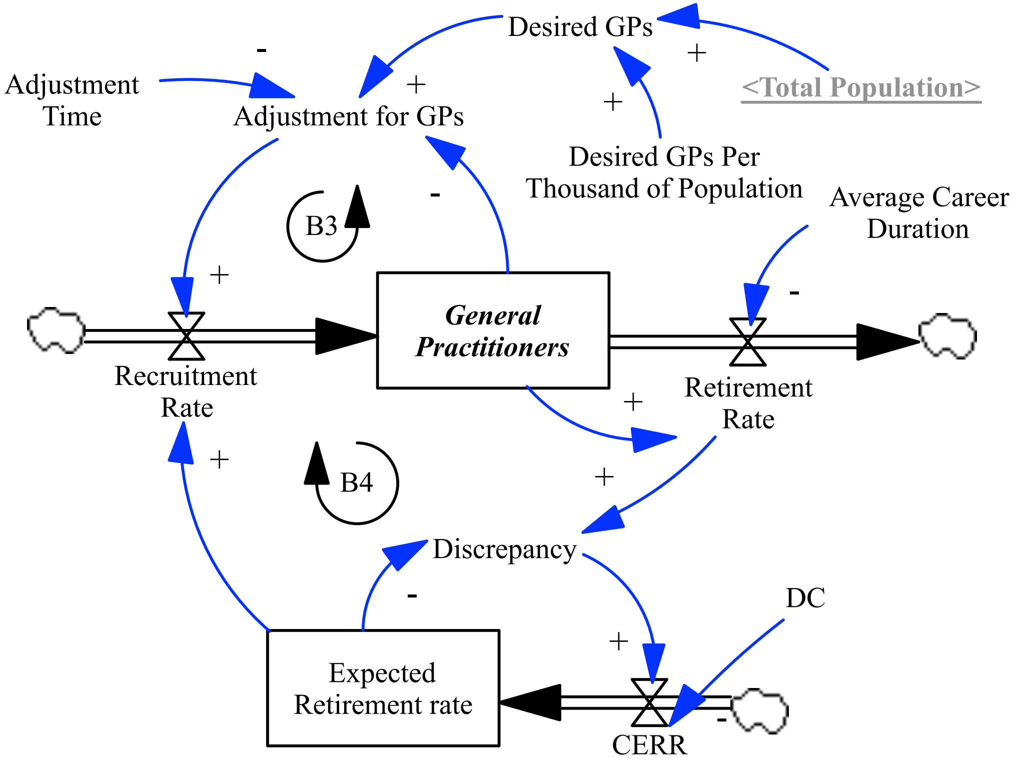


$$Expected\ Retirement\ Rate = INTEGRAL(CERR, 100) \quad (4\text{-}65)$$

$$CERR = Discrepancy\ /\ DC \quad (4\text{-}66)$$

$$DC = 3 \quad (4\text{-}67)$$

$$Discrepancy\ = Retirement\ Rate - Expected\ Retirement\ Rate \quad (4\text{-}68)$$

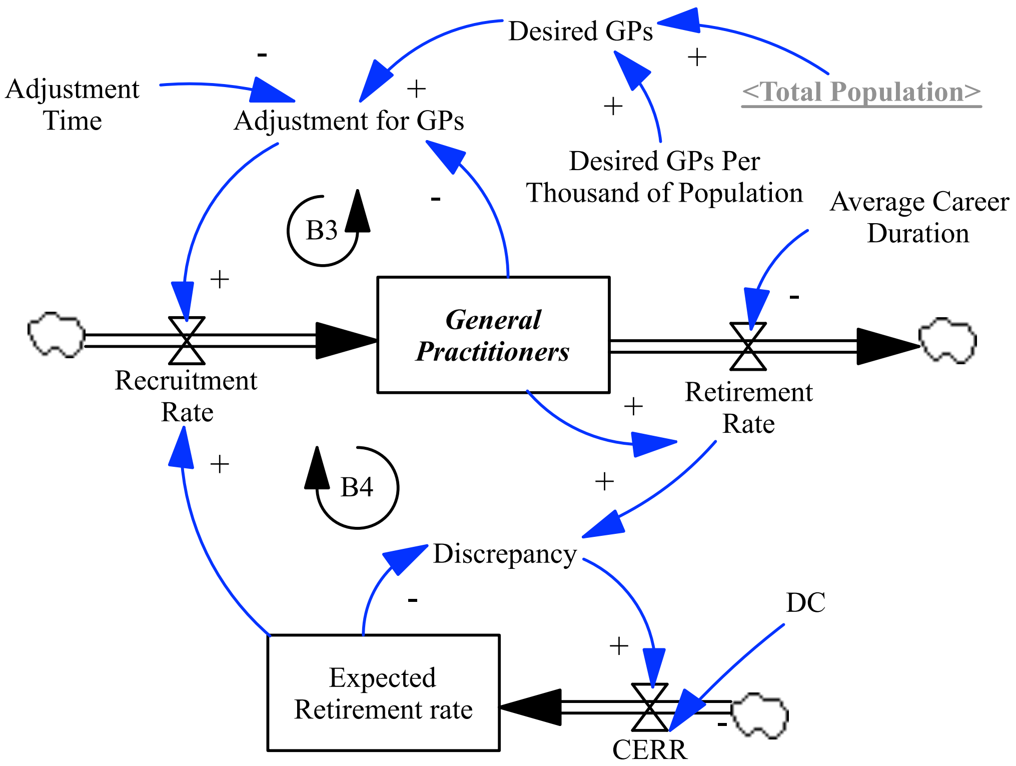


$$Desired\ GPs = Total\ Population \times Desired\ GPs\ Per\ Thousand\ of\ Population \tag{4-69}$$

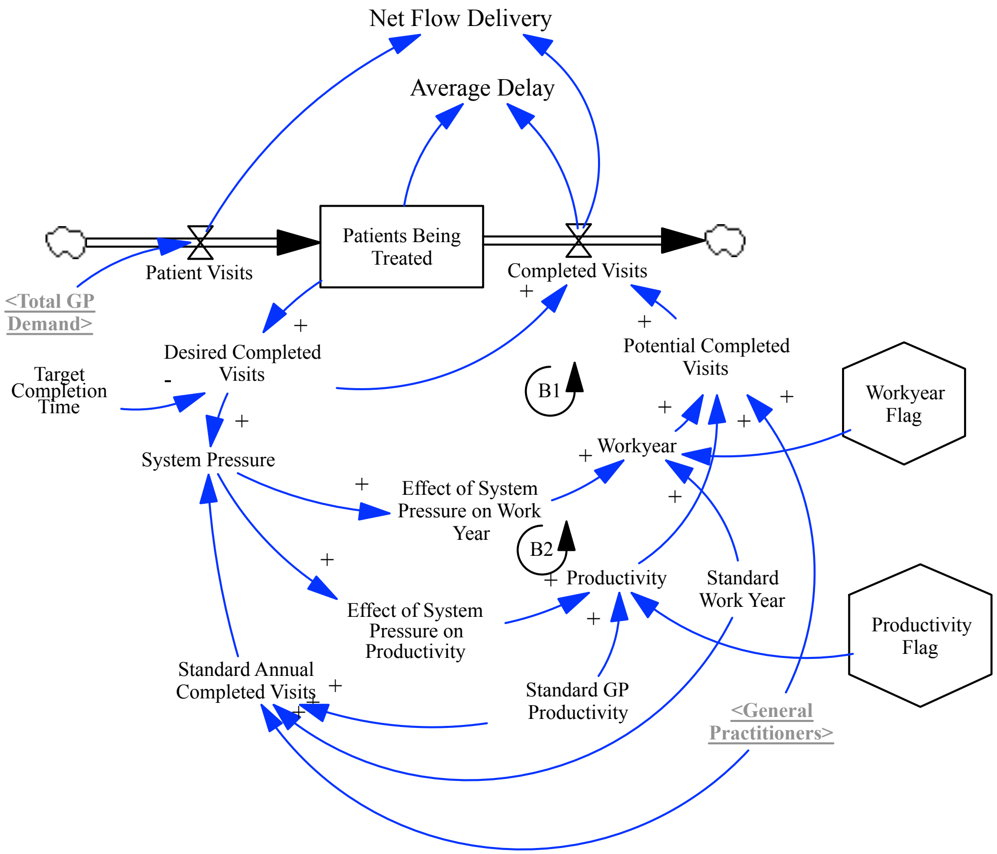
$$Desired\ GPs\ Per\ Thousand\ of\ Population = 0.8/1000 \tag{4-70}$$

$$Adjustment\ for\ GPs = \frac{(Desired\ GPs - General\ Practitioners)}{Adjustment\ Time} \tag{4-71}$$

$$Adjustment\ Time = 5 \tag{4-72}$$



$$Recruitment\ Rate = MAX(0, Expected\ Retirement\ Rate + Adjustment\ for\ GPs) \tag{4-73}$$



$$Workyear = IF\ THEN\ ELSE(Workyear\ Flag = 1,\ Effect\ of\ System\ Pressure\ on\ Work\ Year * Standard\ Work\ Year, Standard\ Work\ Year) \tag{4-74}$$

$$Productivity = IF\ THEN\ ELSE(Productivity\ Flag = 1,\ Effect\ of\ System\ Pressure\ on\ Productivity * Standard\ GP\ Productivity,\ Standard\ GP\ Productivity) \tag{4-75}$$

Three Scenarios

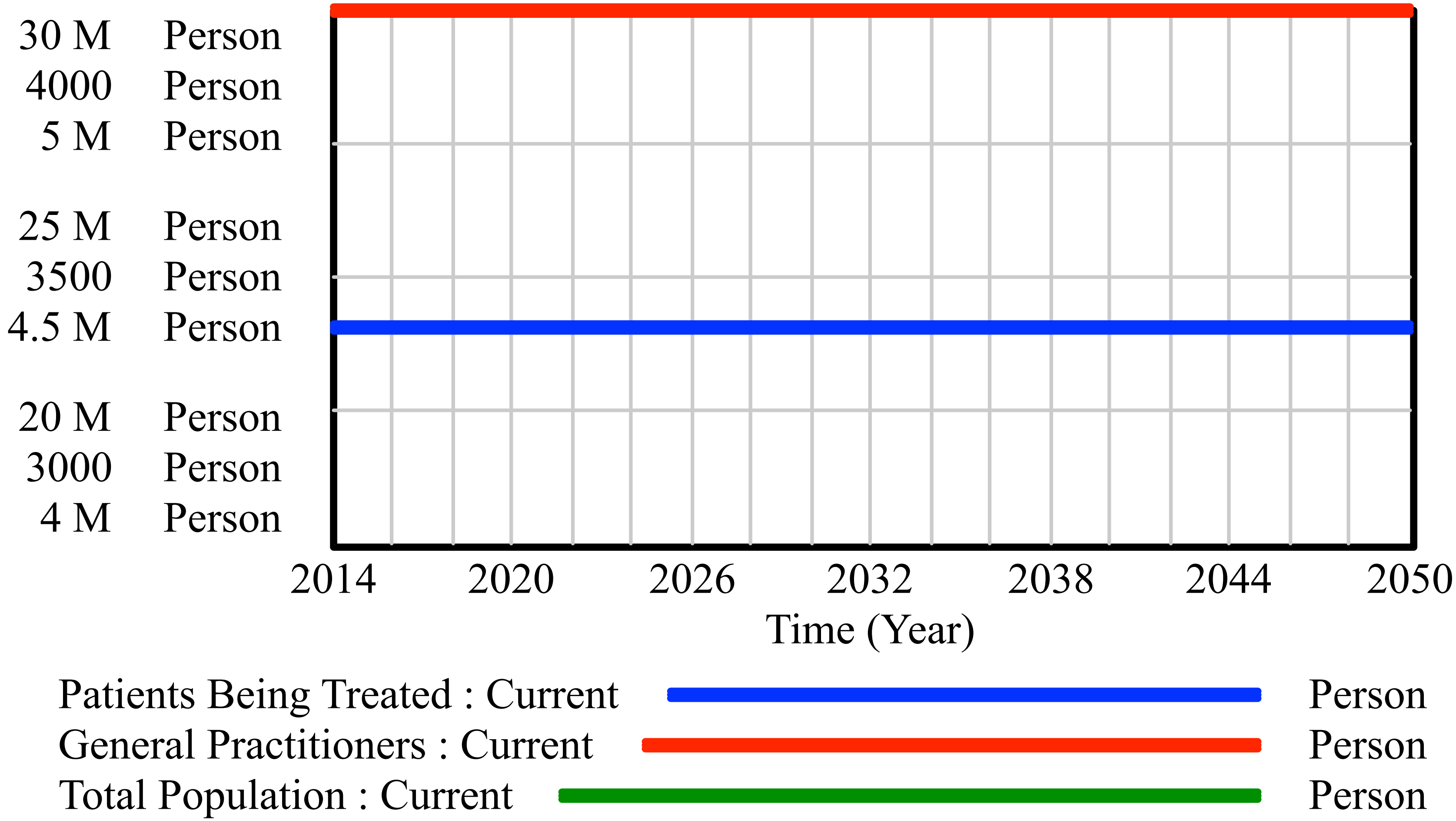
Number	Name	Description
1	Equilibrium	No growth or decline in population and all cohorts remain constant.
2	Population growth and Aging – No Response	Population grows with associated growth in practitioners. However, pressure-relieving feedback loops are not active
3	Population growth and Aging – With System Response	Population grows with associated growth in practitioners. Pressure-relieving feedback loops are active

Initial Capacity & Demand

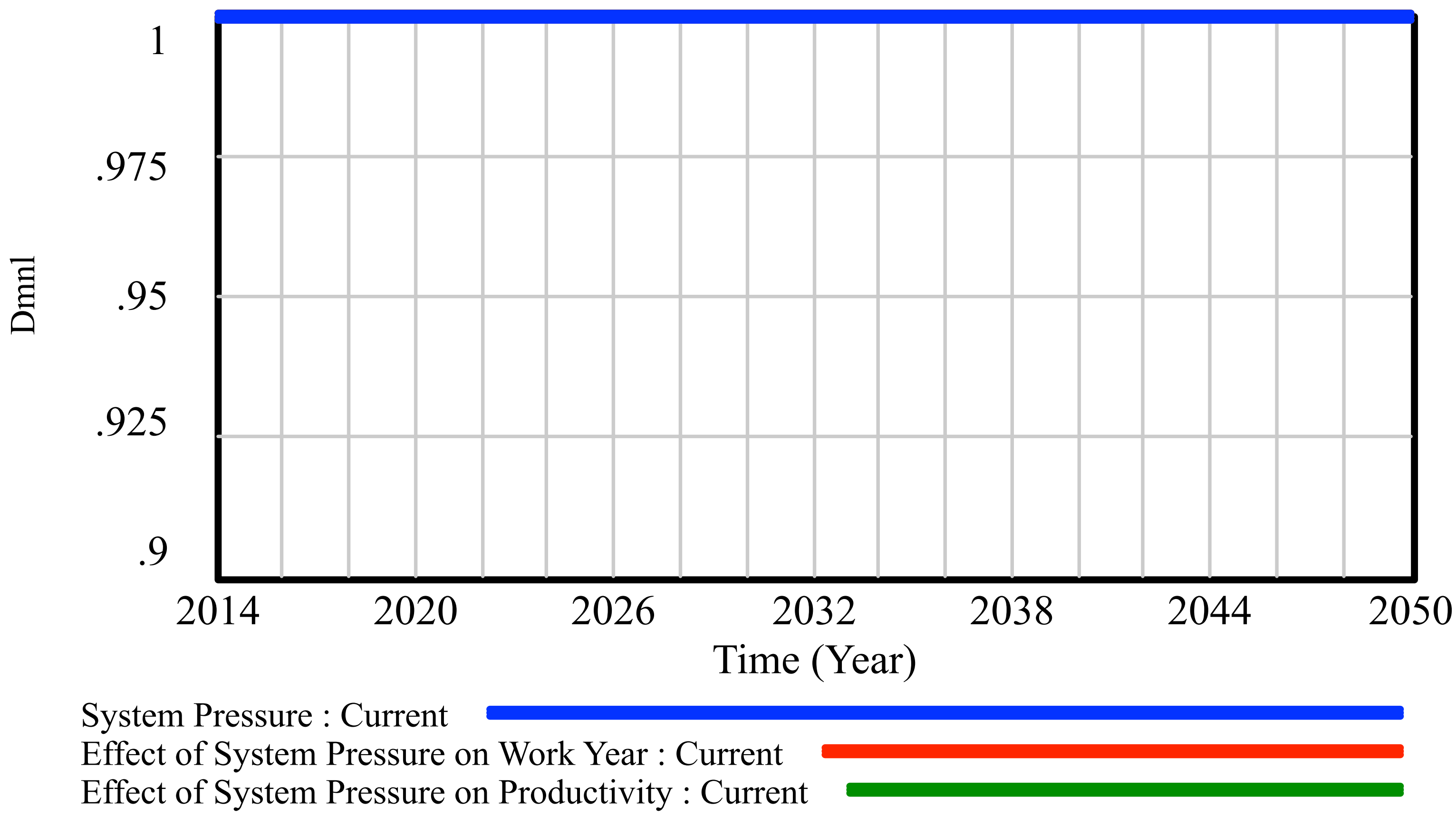
Standard GP Productivity	24 patients/GP/day
Standard Work Year	250 days/year
General Practitioners	4,000 GPs
Standard Annual Capacity	24,000,000 patients/year

Cohort	**Initial Value**	**Average Visits**	**Initial Visits**
$Population_{0\text{-}14}$	1,000,000	3	3,000,000
$Population_{15\text{-}39}$	1,500,000	4	6,000,000
$Population_{40\text{-}64}$	2,000,000	5	10,000,000
$Population_{65+}$	500,000	10	5,000,000
Total Initial Visits			24,000,000

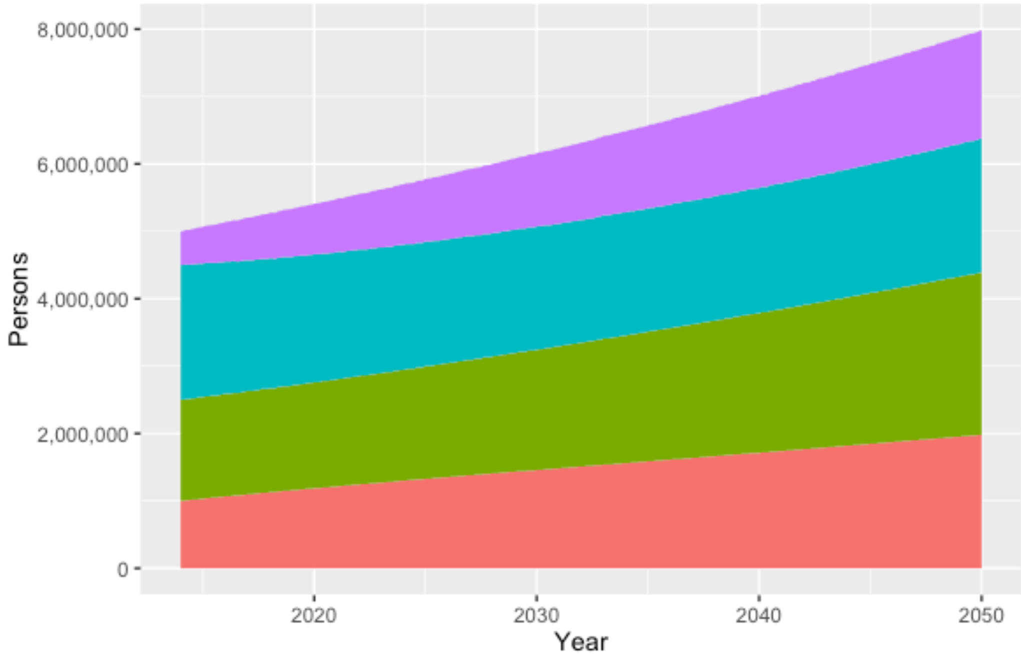
Scenario 1: Stocks



Scenario 1: Pressure Indicators

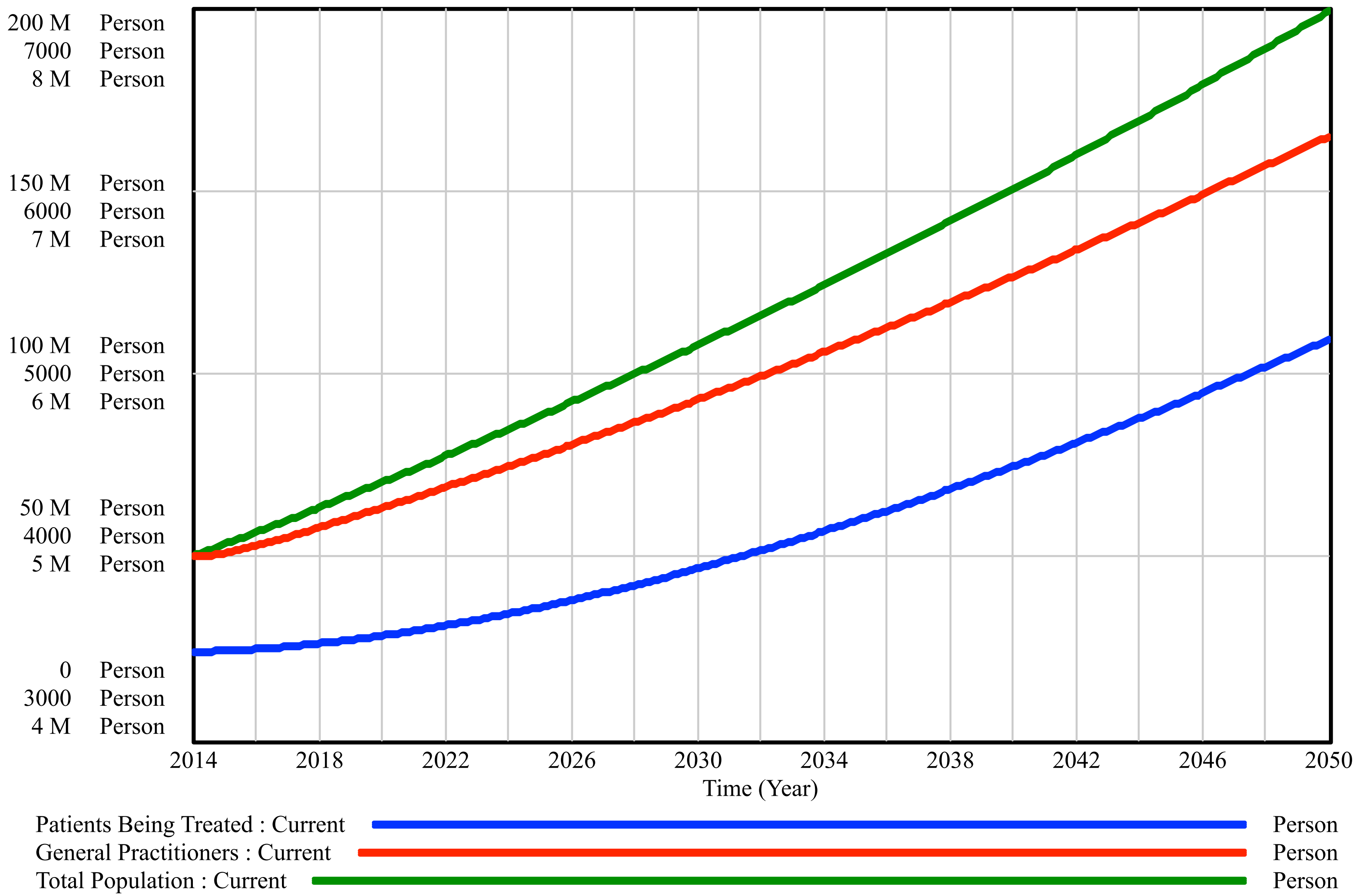


Snapshots of a growing population

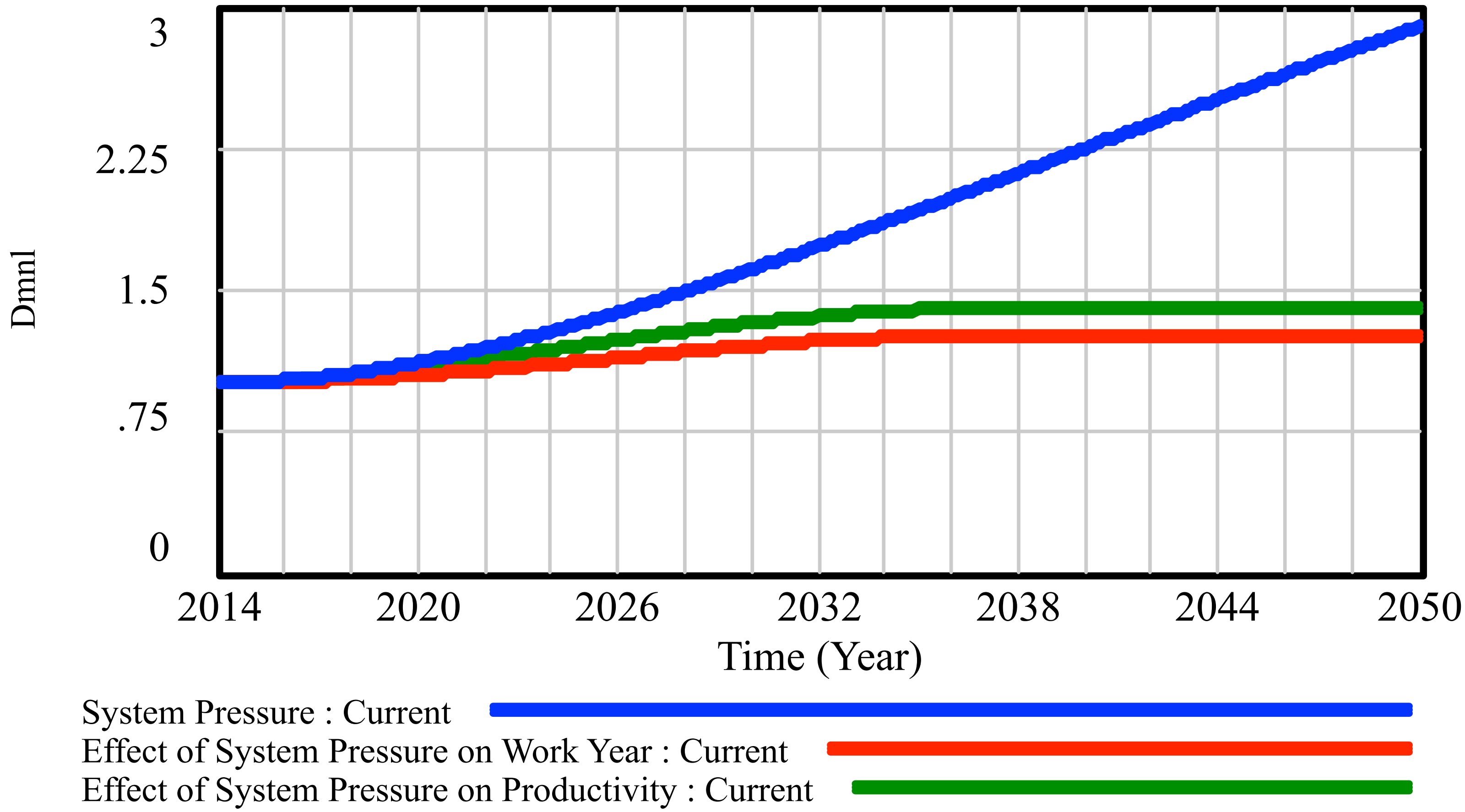


Year	Population$_{0\text{-}14}$	Population$_{15\text{-}39}$	Population$_{40\text{-}64}$	Population$_{65+}$
2014	20%	30%	40%	10%
2025	23%	29%	32%	16%
2035	24%	29%	28%	19%
2050	25%	30%	25%	20%

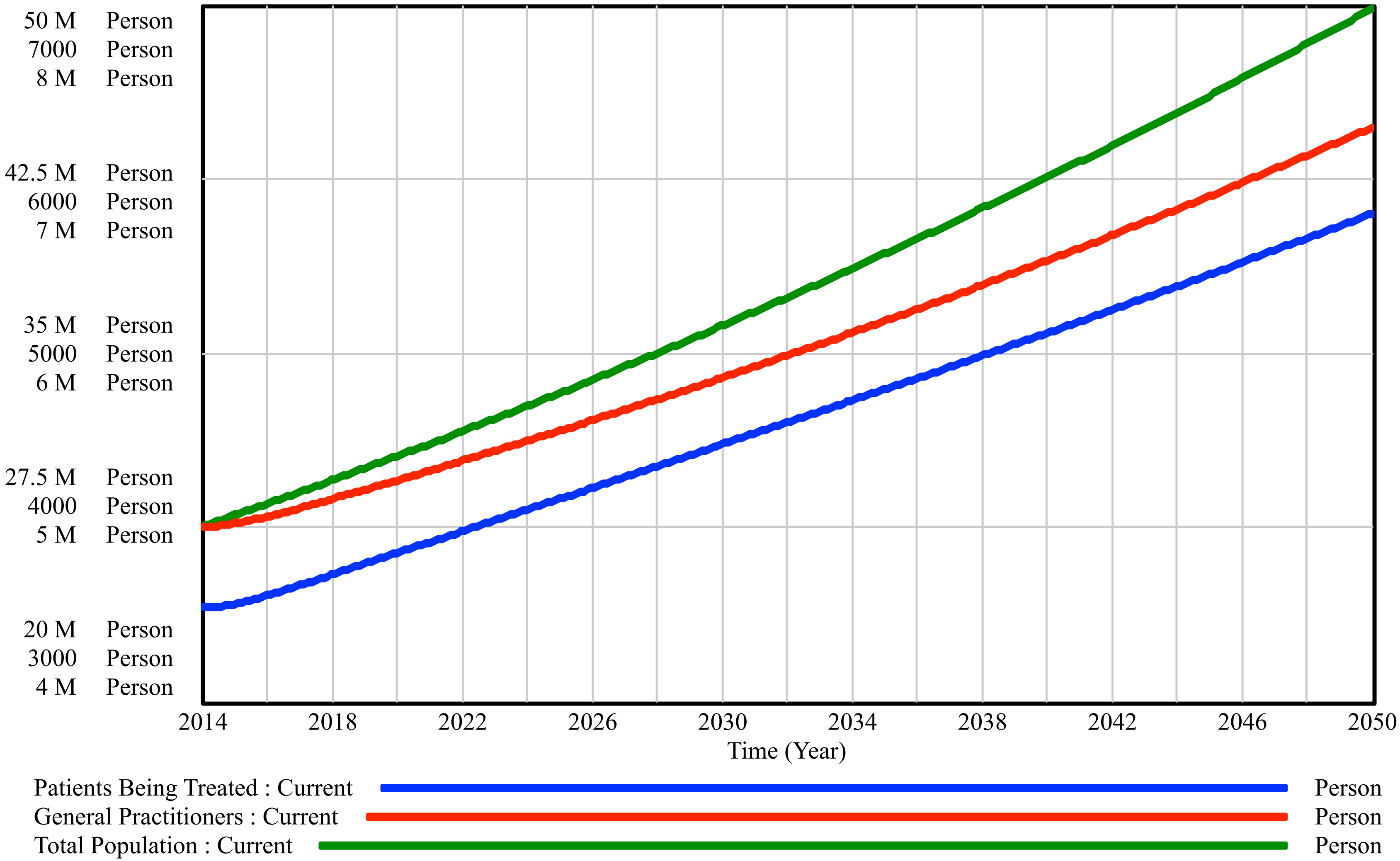
Scenario 2: Stocks



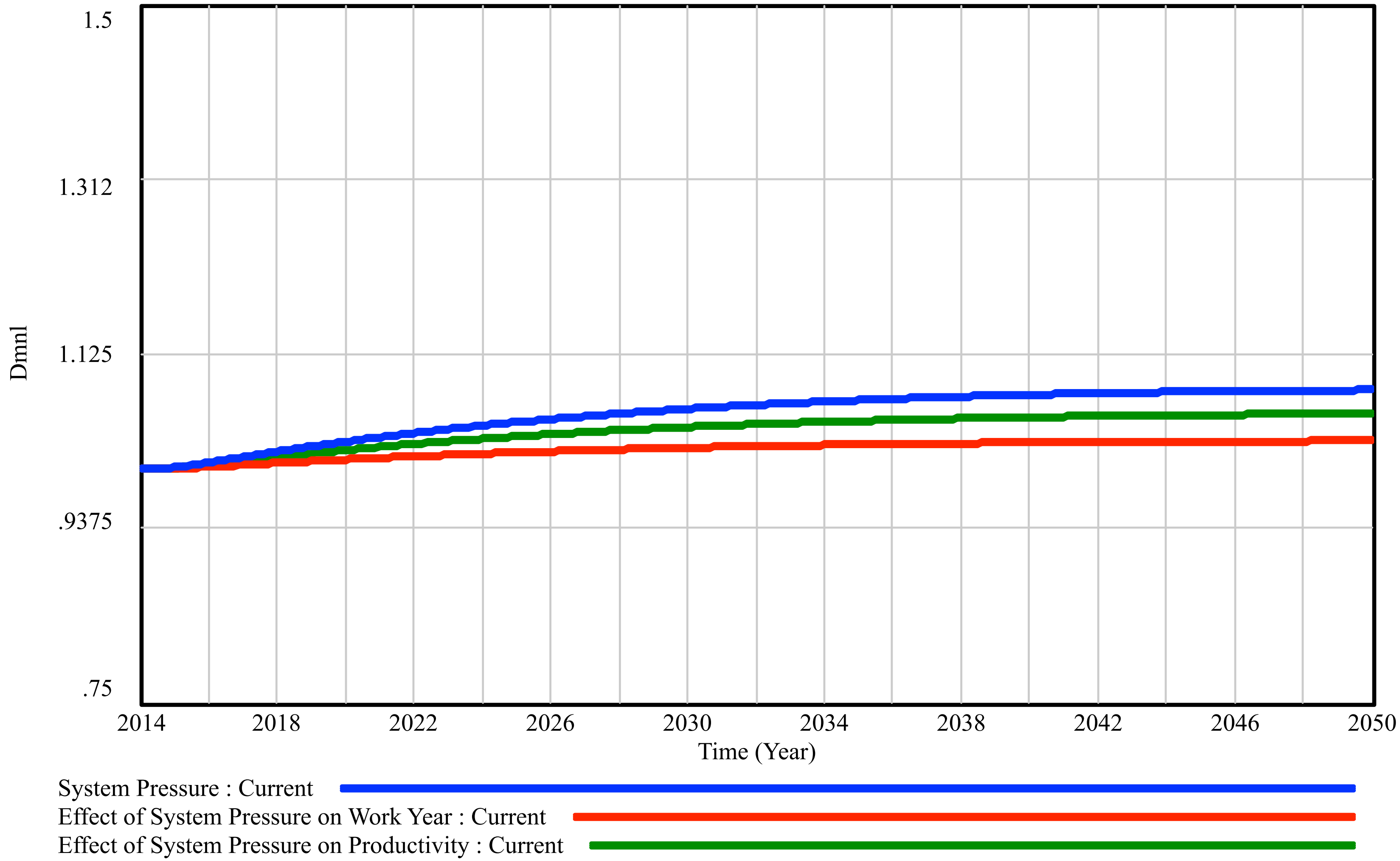
Scenario 2: Pressure Indicators



Scenario 3: Stocks

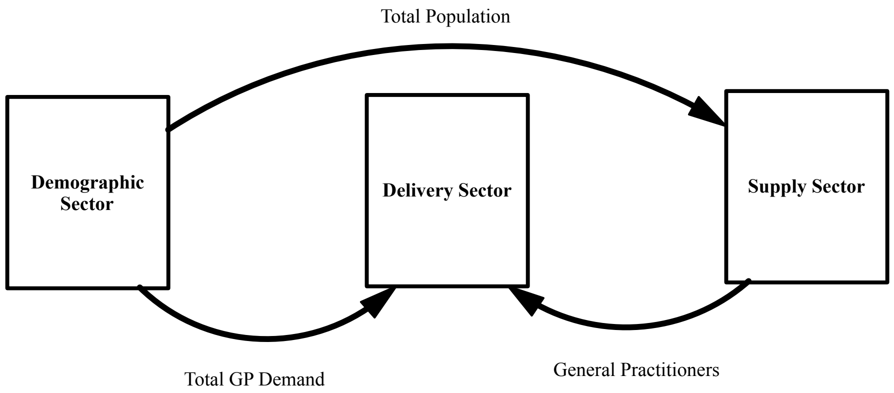


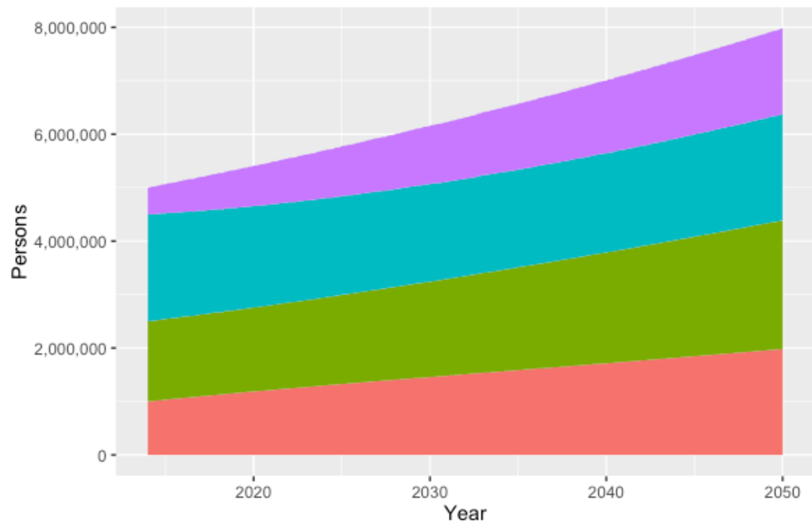
Scenario 3: Pressure Indicators



Conclusion

- Integration of sectors, and model constructs:
  - Aging chain, through first order delays
  - Resource management, with the stock management structure
  - Capacity constraints and effects driving the balancing feedback loops for increasing capacity.





Challenge 10.1

(c) Consider the following dynamics for a smartphone product.

- As **product quality** increases, so too does **product attractiveness**. On the other hand, an increase in **delivery delay** reduces product attractiveness.
- An increase in product attractiveness leads to increased **demand**, which results in (1) increased **production pressures** and (2) further **investment in process improvement**.
- Production pressures and process improvement impact both product quality and delivery delay.

Construct a causal loop diagram for this scenario, and identify loop and link polarities. Based on the calculated loop polarities, recommend a strategy for the company to cope with increasing product demand.

Challenge 10.2

(b) Construct a stock and flow model from the following description for a company (there is no requirement to add equations to the model).

- The customer base increases when new customers are recruited, and decreases when customers are lost.
- Company staff levels increase with new hires, and reduce with people leaving.
- The customer to staff ratio is a ratio of customers (numerator) to staff (denominator).
- As the customer staff ratio increases, the company attractiveness declines.
- An increase in company attractiveness leads to more new customers.
- An increase in the customer staff ratio leads to an increase in the hire rate for new staff.
- An increase in customer staff ratio leads to a decrease in staff morale.
- An increase in staff morale causes a decrease in people leaving.