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Markus Vomhof[1]

Hospital Competition with Heterogeneous Patient Groups – Incentives and Regulation

Abstract

Competing hospitals may not only use quality of service to attract patients but also their specialization profile. Applying a Hotelling-duopoly and interpreting respectively quality and specialization as vertical and horizontal differentiation, we analyze the optimal allocation in both dimensions for hospitals. To account for heterogeneity in preferences as well as in the health status, two patient groups are introduced. These groups differ in two parameters, (i) treatment costs and (ii) preference for a good match between patients' needs and hospitals' specialization profile. Moreover, we derive the optimal reimbursement scheme a regulator is able to achieve. The results show that the hospitals' specialization decision is determined mainly by two relations: which group is more profitable for hospitals and which group is endowed with the higher preference for a good match. The reimbursement scheme a regulator implements deviates from a pure cost partitioning scheme. In particular, the regulator aims at inducing higher quality by exploiting the heterogeneity in preferences.

JEL Classification: I11, I18, L13

Keywords: Hospital competition; heterogeneity; hotelling-duopoly; regulation

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1. Introduction

A clear trend of recent health care reforms in OECD countries is the intention to improve efficiency of health care providers which means reducing health care expenditures at a constant or improving level of quality. In this sense, the introduction of prospective payment systems like diagnosis related groups (DRGs) incentivizes hospitals to reduce inefficiencies and treatment costs yet also decrease financial power of hospitals.[1] Reforms of the English National Health Service (NHS) in 2006 as well as reforms in the Netherlands, Denmark, Sweden and Norway broaden the opportunities for patients to choose between hospitals and aim at stimulating competition between health care providers (Propper et al, 2006).[2] Furthermore, the Statutory Health Insurance Modernization Act of 2004 and the Statutory Health Insurance Competition Strengthening Act of 2007 in Germany intend to foster competition between health care providers by putting competitive pressure on health insurance companies which they, in turn, transfer to health care providers (Lisac et al., 2010).

As a consequence of these reforms, the hospital market is subject to ongoing restructurings like mergers, acquisitions or closures where hospitals aim at realizing efficiency gains by consolidations and inefficient hospitals exit the market.[3] At the same time, hospitals become more specialized which is reflected by an increase of single-specialty hospitals (Eastaugh, 2001; Schneider et al., 2008) or by a reduction of product lines, i.e. the output mix of cases.[4] Schneider et al. (2008) report an increase of single-specialty hospitals (e.g. surgical, cardiac or orthopedic hospitals) between 2000 and 2005 by 16% for the US which were typical for-profit and physician owned.

It is an ongoing debate whether single-specialty or specialized hospitals increase efficiency due to better employment of resources in terms of economies of scale and (dis)economies of scope than their general competitors or adjust their case mix only to skim the most profitable cases. While studies advocating specialty hospitals underline that they increase welfare improving competition with general hospitals, patient satisfaction and efficiency, studies arguing against specialty hospitals point out that they tend to

[1] See for example Schreyögg et al. (2006) and O’Reilly et al. (2012) for a comparison of prospective payment systems in Europe.
[2] Gaynor et al. (2013) report an improving effect on quality of care for the NHS reform in 2006 while health care expenditures remain stable.
[3] Empirical evidence shows that mergers can indeed generate cost savings (Dranove and Lindrooth, 2003; Harrison, 2011) or increase technical efficiency (Groff, 2007) yet increase also the market power of merged hospitals.
[4] Since hospitals could use the reorganization process after a merger to adjust their product lines, market consolidation may even enhance the emergence of specialty hospitals. Blank and Merkies (2004) point out that hospital mergers in the Netherlands lead to a substantially increase of physicians employed in the merged entity which could be used for post-merger specialization.

attract more healthier patients and limit beneficial cross-subsidizing of unprofitable cases in general hospitals (cf. Barro et al., 2006; Greenwald et al., 2006, Schneider et al., 2008; Carey et al., 2011, 2015). Evidence of the impact of single-specialty hospitals on efficiency is mixed (see Trybou et al., 2014, for a review). Barro et al. (2006) investigate market access of cardiac specialty hospitals and find a reduction in cardiac spending while quality indicators remain stable. Yet, they also show that specialty hospitals attract rather healthier patients than general hospitals. In contrast to the results in Barro et al. (2006), Carey et al. (2008) highlight that surgical and cardiac specialty hospitals are significantly less cost-efficient than the general hospitals they compete with. More recently, Carey et al. (2015) find no evidence for economies of scale or economies of scope for orthopedic and surgical single-specialty hospitals in comparison with their general counterparts. Focusing on specialization with regard to the output-mix of 324 California hospitals in 2003 rather than on single-specialty hospitals exclusively, Gaynor et al. (2015) find economies of scope for primary care and diseconomies of scope for secondary and tertiary care which indicates that hospitals can use specialization to increase efficiency regarding to the type of care (secondary and tertiary). Herwartz and Strumann (2012) capture the degree of specialization by an Information Theory Index that relates the shares of hospitals' cases to the national average in Germany. The results of their Data Envelopment Analysis and Stochastic Frontier Analysis show that specialization decreased efficiency from 1995 to 2001 and increased efficiency from 2002 to 2006.[5] Lindlbauer and Schreyögg (2014) use the same database and find mixed results how specialization affects efficiency since the results depend mainly on the applied specialization measure.

Furthermore, specialization is relevant with respect to the reimbursement system since hospitals can use their specialization profile to select higher profitable patients. In general, hospitals can exploit the payment system if it does not reflect heterogeneity of patients perfectly by upcoding patients in DRGs with higher reimbursement (Dafny, 2005).[6] Besides upcoding, hospitals could be able to adjust their output mix of cases towards more profitable DRGs by specialization. This is supported by Liang (2015) who considered 268 Taiwan hospitals over a period from 1999 to 2004 and finds that hospitals increase the share of profitable orthopedic DRGs in their case mix. Thus, hospitals are able to use their specialization profile to increase profits at the expense of less profitable production lines whereat specialization provides the argument for treating mostly patients that match the hospitals' expertise. If

[5] The observed pattern is less clear for the Stochastic Frontier Analysis whereat the effect of specialization on efficiency is positive for 1995 and 1996.

[6] Cream-skimming (overprovision of services for patients with less complex shape of the disease and underprovision of services for patients with high complexity) and dumping (avoidance of patients with complex shape of the disease) are also possibilities to select patients (Ellis, 1998).

hospitals cannot adjust the output mix due to their status as general hospitals or as teaching hospitals, they have to provide less profitable or even unprofitable treatments in their output mix resulting in a worse financial performance than specialized hospitals. Furthermore, patients incur high search costs and probably high travel costs to receive a treatment corresponding to their needs.

In this study, we analyze whether hospitals competing for heterogeneous patients by quality can adjust their specialization profile to reduce competitive pressure. In particular, to model competition we apply a Hotelling-duopoly (Hotelling, 1929) with endogenous horizontal differentiation and endogenous vertical differentiation and interpret the former as specialization and the last as quality. Patients vary in their specialization preferences determined by the disease they suffer from. This is captured by the patient's position on the Hotelling-line whereat diseases and specialization needs coincides. Furthermore, we distinguish between two groups of patients depending on the degree of complexity of their disease. Complexity captures that patients that suffer from the same disease may differ according to severity and comorbidity connected to the main diagnosis. In particular, for each different disease on the Hotelling-line there is a patient that suffer from a high complex shape of this disease and a patient that suffer from a low complex shape. We allow that the two groups may differ in their preference for a good match between patients' needs and hospitals' specialization profile as well as in treatment costs and in treatment prices. In general, the heterogeneity of patients justifies differences in the hospitals' specialization to respond optimally to patients' needs. Yet, differentiation in specialization makes hospitals less comparable which may result in less quality effort. Furthermore, we introduce a regulatory authority that is able to set treatment prices yet not quality or specialization of hospitals directly. We want to analyze whether the regulator can implement a price scheme that is welfare improving in comparison to a scheme where treatment prices equal treatment costs which is associated with a DRGs system.

This work contributes to the theoretical literature that models hospital competition along two dimensions and extends it by introducing heterogeneous patient groups that respond to quality and specialization of hospitals. Even if most papers understand horizontal differentiation either as geographical location (Bardey et al., 2012) or specialization (Economides, 1989; Calem and Rizzo, 1995; Brekke et al.; 2007) results do not rely on this interpretation. While our model is similar to Brekke et al. (2006) and Bardey et al. (2012) in focusing on the interaction of quality and specialization in an approach where treatment prices are determined by a regulator, both papers do not account for heterogeneity of patient groups according to complexity, preferences and costs which could be used to reduce financial pressure by exploiting the reimbursement system. Brekke et al. (2006) analyzes the interaction of two strategic variables of firms, quality and geographical location (which they also assume to be interpretable as specialization), in a Hotelling model given that prices are set by a benevolent regulator.[7] They find that quality competition is intensified if firms locate close to each other (sell easy substitutable products) and reduce competitive pressure the further apart firms locate (the less substitutable products are). In general, the regulator cannot achieve the first best solution by only adjusting prices. The second best solution is characterized by underinvestment in quality and large horizontal differentiation if transportation costs are sufficiently small and by overinvestment in quality and low horizontal differentiation if transportation costs are sufficiently high. Bardey et al. (2012) extend the framework of Brekke et al. (2006) by introducing fixed and variable costs depending on quality in the hospitals' cost function which they use to study the effect of mixed payment systems when hospitals can choose quality and location under price regulation. Using just a pure prospective payment system, the regulator is not able to implement the first best solution. Yet, the regulator can improve the quality-location-allocation if it is allowed to reimburse variable cost in addition, i.e. the regulator determines the prospective price and the cost reimbursement rate. Considering patients that differ with respect to preferences, Brekke et al. (2011) apply a Salop-model to analyze quality competition. Yet, their work differs from ours since the research question centers mainly on the aspect of altruism and how it affects hospital quality provision.

We find that hospitals seek to attract the more profitable group. If the more profitable group is endowed with a higher preference for a good match, hospitals tend to locate closer to the center of the distribution. Otherwise, if the more profitable group has a higher responsiveness for quality, hospitals choose a higher quality level. In order to compensate fiercer quality competition they choose a greater distance. A regulator can take advantage of this behavior and induce higher quality as well as a shorter distance to the center of the patients' distribution than under a cost partition scheme that makes one group as profitable as the other group.

This paper is organized as follows. In section 2, the assumptions of the model are described. In section 3 the Nash-equilibrium in qualities and in section 4 the Nash-equilibrium in specializations are determined and discussed. Introducing a regulatory body, section 5 analyzes optimal price setting policy. Section 6 concludes.

[7] Even if Brekke et al. (2006) do not restrict their analysis to hospitals they point out that the health care market is a typical example of their model.

2. The model

Patients are assumed to suffer from different diseases that can be treated in each of two hospitals $j = \{0,1\}$. Moreover, patients are uniformly distributed between 0 and 1 on the Hotelling-line according to their specialization preferences, $y \in [0,1]$, with total mass normalized to 1. Every patient demands one single treatment. Hospitals respond to the patients' needs by choosing a specialization location. Patients always prefer shorter distances from their needs to the hospitals' specialization and higher treatment qualities which is reflected in an additive separable utility function in the quality of receiving treatment in hospital j, q_j, and in the squared distance between the hospitals specialization, s_j, and patient y's needs.

$$u_i(q_j, s_j) = v_i + \alpha \cdot q_j - \beta_i (y - s_j)^2, \qquad i = \{A, B\} \text{ and } j = \{0,1\} \tag{1}$$

The gross valuation, v_i, that represents the utility induced by the treatment itself is assumed to be sufficiently large to ensure that all patients demand treatments. Marginal utility of quality and marginal utility of distance is α and β_i, respectively, whereat the marginal utility of distance can also be interpreted as an intensity parameter for a good match. We differentiate between two groups of patients, indexed by $i = \{A, B\}$, that differ in (i) the preference for a good match[8], β_i, and (ii) the treatment costs, c_i.[9] To illustrate the difference between groups, a patient of one group is interpreted to suffer from a more complex variant of a disease than the equivalent patient of the other group.[10] Patients' behavior is not affected by prices due to full coverage of inpatient care by a statutory health insurance. To derive the hospitals' demand, we calculate the specialization need of the patient that is indifferent between receiving treatment in hospital 0 or hospital 1, $\tilde{y}_i$.[11]

$$\tilde{y}_i = \frac{1}{2}(s_0 + s_1) + \frac{\alpha(q_0 - q_1)}{2\,\beta_i(s_1 - s_0)}, \qquad i = \{A, B\} \tag{2}$$

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[8] Heterogeneity in preferences can be expressed in both, the preference for a good match and the preference for quality. It is not necessary to vary both parameters with respect to patient groups since they are related linearly to each other by the utility function.

[9] We allow patients to differ in the gross valuation as well. Since v_i is canceled out by deriving the demand, hospital behavior is independent of the gross valuation.

[10] A priori, we do not assume any relation between c_A and c_B or between β_A and β_B. In general, we cannot assure that higher complexity induces a higher preference for a good match. It could be possible that patients suffering from a complex disease wish to receive treatments in a hospital with overall higher quality and evaluate the specialization match as less important. In order to account for both possibilities, we use an approach as flexible as possible.

[11] If both hospitals choose the same specialization, the second term in equation (2) is undefined. Then, it is assumed that all patients receive their treatments in the hospital that chooses higher quality and if both hospitals choose the same quality level, the total demand is equally divided between both hospitals.

We do not restrict hospitals' specialization choices on the $[0,1]$-interval since specializations outside the patients interval have a meaningful interpretation as "over-specialization".[12] Without loss of generality, it is assumed that hospital 0 always locates left hand side of hospital 1, i.e. $s_0 < s_1$. Using the indifferent patient's position, equation (2), we specify the demand for hospital j, D_j, as the sum of the demands for treatments in hospital j for group A and group B. Note that the respective shares of group A and group B in the population are λ and $(1-\lambda)$.

$$\begin{aligned} D_0 &= D_{0A} + D_{0B} = \lambda \cdot \tilde{y}_A(q_0, q_1, s_0, s_1) + (1-\lambda) \cdot \tilde{y}_B(q_0, q_1, s_0, s_1) \\ D_1 &= D_{1A} + D_{1B} = \lambda \cdot \big(1 - \tilde{y}_A(q_0, q_1, s_0, s_1)\big) + (1-\lambda) \cdot \big(1 - \tilde{y}_B(q_0, q_1, s_0, s_1)\big) \end{aligned} \tag{3}$$

The hospitals receive a treatment price, p_i, for treating a patient of type i which generates costs equal to $c_i \cdot q_i$ per treatment at a given quality level for the hospitals.[13] The per capita profit margin of group i for hospital j then is $p_i - s_i \cdot q_j$ and the profit of hospital j is as follows.

$$\pi_j = \big(p_A - c_A \cdot q_j\big) \cdot D_{jA}(\cdot) + \big(p_B - c_B \cdot q_j\big) \cdot D_{jB}(\cdot), \qquad j = \{0,1\} \tag{4}$$

Hospitals cannot discriminate between groups by setting different quality levels since we assume that quality is a non-excludable good. This is justified since groups actual suffer from the same diseases yet differ in complexity of these diseases. For instance, a cardiologist's advanced training benefits patients with complex and less complex heart diseases or improving hygiene avoids infections for all patients.

The choice of quality and specialization is modeled as a sequential three stage game:

Stage 1: The regulator sets treatment prices for the groups, p_A and p_B.

Stage 2: The hospitals choose their specialization, s_0 and s_1.

Stage 3: The hospitals determine the quality level, q_0 and q_1.

The game structure implies that quality is a strategic variable adjustable in the short-term whereas the specialization cannot be changed in the short-term. In addition, a feasible equilibrium is an equilibrium

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[12] Due to avoidance of corner solutions, this assumption also simplifies the calculation of the specialization equilibrium.

[13] Following Bardey et al. (2012), we assume that the variable cost of providing one unit of treatment depends on the level of quality. Models like Brekke et al. (2006, 2007) that do not rely on this assumption are characterized by first order conditions which are independent of the rival's quality in the quality subgame implying that the quality decision is not a strategic choice since the hospital can determine its optimal quality without consideration of the rival's quality.

that induces non-negative profits for hospitals at a non-negative level of quality and prices. The game is solved by backward induction.

3. Quality equilibrium

In stage 3 of the game, each hospital maximizes its profit, equation (4), with respect to quality at given specializations and treatment prices.[14] The first order condition of the profit maximum stated in equation (5) requires that marginal revenues and marginal costs of quality provision have to be equal.[15]

$$\frac{\partial \pi_j}{\partial q_j} = \sum_{i=\{A,B\}} -c_i D_{ji}(q_0, q_1, s_0, s_1) + (p_i - c_i q_j)\frac{\partial D_{ji}(q_0, q_1, s_0, s_1)}{\partial q_j} = 0, \qquad j = \{0,1\} \tag{5}$$

Note that the first order condition depends on the hospital's own quality and on the rival's quality. To derive the Nash equilibrium in qualities, we solve the reaction functions[16] for the respective qualities of hospital 0 and hospital 1, q_0 and q_1 whereat we define $\Delta \equiv s_1 - s_0$ as distance between the hospitals' specializations and $\bar{c} \equiv c_A\lambda + c_B(1-\lambda)$ as the average treatment costs in the population.

$$\begin{aligned} q_0^* &= \frac{\frac{p_A\lambda}{\beta_A} + \frac{p_B(1-\lambda)}{\beta_B}}{\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}} + \frac{-\bar{c}\Delta\frac{1}{3}(2 + s_0 + s_1)}{\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)} \\ q_1^* &= \frac{\frac{p_A\lambda}{\beta_A} + \frac{p_B(1-\lambda)}{\beta_B}}{\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}} + \frac{-\bar{c}\Delta\frac{1}{3}\left(4 - (s_0 + s_1)\right)}{\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)} \end{aligned} \tag{6}$$

Unsurprisingly, if specializations are symmetric to 0.5, i.e. $s_1 + s_0 = 1$, the equilibrium qualities of hospital 1 and hospital 2 are the same. The first term in equation (6) is a price cost relation that weighted prices and costs by the preference for a good match. If the preference for a good match is the same for both groups, the first term simplifies to a ratio of average prices to average costs in the population. The second term captures how the equilibrium quality is affected by specialization differentiation. Under

[14] A priori, a symmetric equilibrium is not assumed even if two identical firms with uniformly distributed patients will induce a symmetric equilibrium. We follow a more careful approach that allows us to determine a distance between the hospitals' specializations.

[15] The second order conditions guarantee a maximum by the convexity of the cost function.

[16] The reaction functions are provided in Appendix A.1.

symmetry in specializations, the second term is always negative and, thus, lowers the equilibrium quality levels.

Next, we analyze the comparative static regarding the Nash equilibrium in qualities. While it is straightforward to show that the optimal quality levels increase in the group specific treatment prices, p_i, the influence of the preference for a good match of group i, β_i, on optimal quality is ambiguous. Yet, applying the implicit function theorem on the first order condition, equation (5), the derivatives gain a meaningful interpretation. The formal approach is stated in Appendix A.2.

$$\begin{aligned} \left.\frac{dq_j}{d\beta_A}\right|_{q_0=q_0^*,q_1=q_1^*} &= \frac{\lambda \frac{\alpha}{\beta_A^2 \Delta}\left(p_A - c_A q_j^*\right)}{SOC}, \qquad j=\{0,1\} \\ \left.\frac{dq_j}{d\beta_B}\right|_{q_0=q_0^*,q_1=q_1^*} &= \frac{(1-\lambda)\frac{\alpha}{\beta_B^2 \Delta}\left(p_B - c_B q_j^*\right)}{SOC}, \qquad j=\{0,1\} \end{aligned} \tag{7}$$

Since the second order condition, i.e. $SOC \equiv \partial^2 \pi_j(\cdot)/\left(\partial q_j\right)^2$, is negative, it follows from equation (7) that a higher preference for a good match reduces the optimal quality level as long as the profit margin is positive. Thus, hospitals account for the patients' preferences if the considered group is profitable. A higher preference for a good match is induced by patients that shift more weight on a good specialization match than on quality. If a patient group becomes more responsive to specialization, hospitals reduce quality and, thus, quality related cost of treatment provision given that this group is still profitable.

To understand the relationship of the strategic variables, we investigate the interaction of quality and specialization. Initially, we consider the influence of a change in the rival's quality, q_{-j}, on the hospital's own quality, q_j. Applying the implicit function theorem to the first order condition, equation (5), and exploiting that $\partial^2 D_{ji}(\cdot)/\left(\partial q_j \partial q_{-j}\right) = 0$ has to hold due to the linear specification of quality in the utility function, the following equation is obtained that describes the slope of the reaction functions.

$$\frac{dq_j}{dq_{-j}} = -\frac{\frac{\partial^2 \pi_j(\cdot)}{\partial q_j \partial q_{-j}}}{\frac{\partial^2 \pi_j(\cdot)}{\left(\partial q_j\right)^2}} = \frac{-c_A \frac{\partial D_{jA}(\cdot)}{\partial q_{-j}} - c_B \frac{\partial D_{jB}(\cdot)}{\partial q_{-j}}}{SOC} = \frac{1}{2} \tag{8}$$

Equation (8) shows that the hospital reacts on a change in the rival's quality by adjusting the own quality half as much as the rival did. How the hospital's quality reacts on a change in the rival's specialization position is stated in equation (9).[17] Appendix A.4 provides a detailed derivation of equation (9).

$$\left.\frac{dq_j}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*} = -\frac{\dfrac{\partial^2\pi_j(\cdot)}{\partial q_j \partial s_{-j}} + \dfrac{\partial^2\pi_{-j}(\cdot)}{\partial q_{-j}\partial s_{-j}} \cdot \dfrac{dq_j}{dq_{-j}}}{\frac{3}{4}SOC} \tag{9}$$

Equation (9) identifies two channels how a change in the rival's specialization affects quality. The *direct effect* is due to the hospital's own quality adjustment in response to the specialization change. In addition, an *indirect effect* influences the equilibrium quality since hospitals account for the adjustment in the rival's quality. The indirect effect depends on the strategic influence between the hospital's and the rival's quality, dq_j/dq_{-j}, that is 1/2. Using the quality equilibrium, equation (6), the explicit derivatives regarding quality changes induced by changes in the specialization position are presented in equation (10).

$$\begin{aligned}
\frac{dq_0^*}{ds_0} &= \frac{2(s_0+1)\,\bar{c}}{3\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)} \begin{cases} \geq 0 \ \ if \ s_0 \geq -1 \\ < 0 \ if \ s_0 < -1 \end{cases} \\
\frac{dq_1^*}{ds_0} &= -\frac{2(s_0-2)\,\bar{c}}{3\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)} \geq 0 \ if \ s_0 \leq 2 \\
\frac{dq_1^*}{ds_1} &= \frac{2(s_1-2)\,\bar{c}}{3\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)} \begin{cases} \leq 0 \ \ if \ s_1 \leq 2 \\ > 0 \ if \ s_1 > 2 \end{cases} \\
\frac{dq_0^*}{ds_1} &= -\frac{2(s_1+1)\,\bar{c}}{3\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)} \leq 0 \ if \ s_1 \geq -1
\end{aligned} \tag{10}$$

Note that the effect of the rival's specialization change s_{-j} on the hospital's quality q_j^* is unambiguous if specializations are symmetric since $s_0 \leq 1/2 \leq s_1$ has to hold for symmetric specializations. Then, a change in the rival's specialization position always increases (decreases) the hospital's quality if the distance between the specialization positions decrease (increase). Analyzing the effect of the specialization of hospital *j* on its own equilibrium quality, we find a threshold that determines the effect of

[17] Determine the effect of a change in s_j on q_j is equivalent and, thus, straightforward to analyze.

specialization on quality which is -1 for hospital 0 and 2 for hospital 1, respectively. Thus, if hospitals choose specialization sufficiently wide apart, i.e. $s_0 < -1$ for hospital 1 and $s_1 > 2$ for hospital 2, the Nash equilibrium quality increases with increasing distance. Otherwise, the Nash equilibrium qualities increase with decreasing distance which means that if hospitals become less differentiated in specializations they must countervail the loss of variety by offering a higher quality level. [18]

4. Specialization equilibrium

In stage 2, hospital j maximizes its profit, equation (4), with respect to the specialization position. The optimal qualities obtained in the quality subgame are inserted in the profit function. Using the envelope theorem and rearrange the expression, we derive the first order condition of hospital j.[19]

$$\frac{\partial \pi_j}{\partial s_j} = \sum_{i=\{A,B\}} \left(p_i - c_i q_j^*\right)\left[\frac{\partial D_{ji}(\cdot)}{\partial s_j} + \frac{\partial D_{ji}(\cdot)}{\partial q_{-j}} \frac{dq_{-j}^*}{ds_j}\right] = 0, \qquad j = \{0,1\} \tag{11}$$

In line with Tirole (2004) and Bardey et al. (2012), the term $\partial D_{ji}(\cdot)/\partial s_j$ is described as *demand effect* and the expression $\left(\partial D_{ji}(\cdot)/\partial q_{-j}\right) \cdot \left(dq_{-j}^*/ds_j\right)$ as *strategic effect*, respectively. The *demand effect* accounts for the immediate influence of a change in the specialization on the market share. In particular, a movement in the direction of the center increases the hospital's demand by a greater hinterland assigned to the hospital. The *strategic effect* accounts for the rival's reaction on a change in the hospital's specialization. The Nash equilibrium in specialization is obtained from the first order condition.

$$\begin{aligned} s_0^* &= \frac{1}{4}\left(\frac{3(\beta_A - \beta_B)\alpha\lambda(1-\lambda)c_A c_B \left[\frac{p_A}{c_A} - \frac{p_B}{c_B}\right]}{\beta_A \beta_B \bar{c}} - 1\right) \\ s_1^* &= 1 - \frac{1}{4}\left(\frac{3(\beta_A - \beta_B)\alpha\lambda(1-\lambda)c_A c_B \left[\frac{p_A}{c_A} - \frac{p_B}{c_B}\right]}{\beta_A \beta_B \bar{c}} - 1\right) \end{aligned} \tag{12}$$

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[18] Assuming symmetric specializations, i.e. $s_0 + s_1 = 1$, a movement in direction of the center induces always higher quality regardless of the current specializations.

[19] The second order conditions are stated Appendix A.3. Under symmetry in specializations, the two second order conditions simplify to $s_0 \geq -2.5$ and $s_1 \leq 3.5$.

Note that the specialization equilibrium is symmetric, i.e. $s_0^* + s_1^* = 1$. Since the specialization of hospital 0 determines that one of hospital 1 and vice versa, we are interested in the distance between the hospitals' optimal specializations, Δ^*, rather than in the single specialization positions.

$$\Delta^* = s_1^* - s_0^* = -\frac{3}{2}\frac{(\beta_A - \beta_B)\alpha\lambda(1-\lambda)c_A c_B\left[\frac{p_A}{c_A} - \frac{p_B}{c_B}\right]}{\beta_A\beta_B\bar{c}^2} + \frac{3}{2} \tag{13}$$

The sign of the first term in equation (13) depends on which group has a higher utility loss by a specialization mismatch, $\beta_A - \beta_B$, and which group is more profitable for hospitals, $p_A/c_A - p_B/c_B$. If the more profitable group has also a stronger preference for a good match, the optimal distance between hospitals' specializations is shorter than 3/2 and larger otherwise. To understand the 3/2 threshold value, note that the first part in equation (13) becomes zero if the patient groups do not differ in either the preference for a good match or in the price cost ratios. Then, the optimal specialization of hospital 0 and hospital 1 is -1/4 and 5/4, respectively and the distance between them is 3/2. In a model that restricts the specialization choice sets on the patient interval this result would be interpreted as maximum differentiation since the distance is greater than one. Yet, in our model this case is an interior equilibrium outside the patient interval which is interpreted as "over-specialization".

In general, the specializations can locate inside or outside the patient interval. Nevertheless, we are interested in the conditions that induce a specialization equilibrium inside the $[0,1]$-interval. These conditions are derived by rearranging equation (13).

$$0 \leq \frac{1}{3}\frac{\bar{c}^2}{\alpha\lambda(1-\lambda)c_A c_B} \leq \frac{(\beta_A - \beta_B)\left[\frac{p_A}{c_A} - \frac{p_B}{c_B}\right]}{\beta_A\beta_B} \leq \frac{\bar{c}^2}{\alpha\lambda(1-\lambda)c_A c_B} \tag{14}$$

While the left part of the inequality reflects that the optimal distance is inside the patient interval, the right part results from the requirement that any distance must be non-negative. Since all variables in the left part are non-negative, a necessary but not sufficient condition for a specialization choice inside the $[0,1]$-interval is that the more profitable group is also endowed with the higher preference for a good match. Otherwise, hospitals will choose specialization positions outside the interval of patients' needs ("over-specialization"). To illustrate this result, consider that the preference for a good match measures the effectiveness of horizontal differentiation. If one group is more responsive to horizontal differentiation and in addition more profitable, hospitals choose specialization locations closer to each other. This behavior is caused by the hospitals' attempt to avoid a loss of profitable patients to their competitors even if they are subject to fiercer quality competition due to a shorter distance. If the more profitable group prefers higher quality than a better specialization match, hospitals seek to attract patients by a higher quality level. Consequential, hospitals countervail a higher quality level by choosing specialization locations at a greater distance.

5. Reimbursement

Next, we focus on the optimal reimbursement scheme in stage 1. A social welfare function is introduced that is the equally weighted sum of patients' surplus and hospitals' profits.[20]

$$\begin{aligned} SWF = \lambda \left[\int_0^{\tilde{y}_A} u_A(q_0, s_0) dy_A + \int_{\tilde{y}_A}^1 u_A(q_1, s_1) dy_A \right] \ldots \\ + (1-\lambda) \left[\int_0^{\tilde{y}_B} u_B(q_0, s_0) dy_B + \int_{\tilde{y}_B}^1 u_B(q_1, s_1) dy_B \right] + \pi_0(\cdot) + \pi_1(\cdot) \end{aligned} \tag{15}$$

As described in section 3, higher treatment prices induce hospitals to choose higher optimal quality levels which improve welfare since higher treatment prices generate no social costs in the social welfare function. Thus, treatment prices have a limit at infinity without further restrictions since the demand is fixed and, thus, do not decline if prices increase. We introduce an exogenous health care sector specific budget labelled by I to account for the limited financial resources. A model with elastic demand side does not require such a restriction due to an amount of patients that would not ask for treatments if prices are sufficiently high. Yet, rejecting patients seems problematic for moral reasons and a budget related to the health care sector is a reasonable assumption. Our focus is on how this exogenous budget is shared between patient groups. The budget condition requires that all expenditures for treatments are less than or equal to the exogenous budget, i.e. $\sum_{i=\{A,B\}} p_i\big(D_{0i}(q_0, q_1, s_0, s_1) + D_{1i}(q_0, q_1, s_0, s_1)\big) \leq I$. Given that all demands are covered, the budget restriction reduces to equation (16).

$$p_A\lambda + p_B(1-\lambda) \leq I \tag{16}$$

[20] The qualitative results do not change if we assume a social welfare function that is a weighted sum between patients' surplus and hospitals' profits and the weighting parameter shifts more or equal weight on the patients' surplus.

5.1. First best solution

As a benchmark case, we analyze the first best solution that maximizes the social welfare function equation (15) with respect to qualities and specializations.[21] To simplify the analysis, we assume a symmetric equilibrium in specializations that induces the same quality for both hospitals.[22] Differentiating the social welfare function with respect to quality and account for symmetry in specializations, yields the first order condition with respect to quality, i.e. $\partial SWF/\partial q_i = (\alpha - \bar{c})/2$. An interior optimum requires that the marginal benefits from a unit quality equal marginal costs (which are identical with the average costs in the population) of the unit quality. Since the first order condition is independent of endogenous variables, marginal benefits and costs will not coincide in general. If costs of quality exceed the benefits from quality, the first best quality is zero. Otherwise, the first best quality is as high as possible. Henceforth, we assume that the marginal benefit of quality is higher than or equal to the marginal costs of quality, i.e. $\alpha \geq \bar{c}$.[23] The highest possible quality level is determined by the quality that induces zero profits for hospitals. For the first best quality, we obtain $q^{fb} = \big(p_A\lambda + p_B(1-\lambda)\big)/\bar{c}$ or $q^{fb} = I/\bar{c}$ since the budget restriction has to hold with equality at the optimum. The respective symmetric first best specializations locate at $s_0^{fb} = 1/4$ for hospital 0 and $s_1^{fb} = 3/4$ for hospital 1. This replicates a standard result of Hotelling-models with uniform distribution of patients between 0 and 1 since these points minimize the distance between hospitals specializations and patients' needs.

5.2. Regulator

Following Brekke et al. (2006) and Bardey et al. (2012), we assume that quality and specialization are non-contractible. Thus, the regulator cannot set specialization and quality directly even if both are fully observable. The regulator maximizes the social welfare function, equation (15), with respect to the treatment prices, p_i, and subject to the budget restriction, equation (16), that has to hold with equality at the optimum.

$$\max_{p_A \geq 0, p_B \geq 0} SWF(q_0^*, q_1^*, s_0^*, s_1^*, p_A, p_B) \qquad s.t.\ p_A\lambda + p_B(1-\lambda) \leq I \tag{17}$$

[21] Each pair of prices that fulfills the budget restriction is a feasible price combination in equilibrium since prices cannot adjust the first best allocation in quality and specialization.
[22] Assuming a symmetric equilibrium is not restrictive since both hospitals are identical and the patients are uniformly distributed.
[23] The case $\alpha < \bar{c}$ is straightforward to analyze.

Solving the first order conditions for prices given the hospitals' optimal quality-specialization-allocation, the optimal reimbursement scheme induced by the regulator is derived.

$$
\begin{aligned}
p_A^r &= I\frac{c_A}{\bar{c}} + \frac{2\bar{c}\beta_A\beta_B}{3\alpha\lambda(\beta_A-\beta_B)}\left(1+\frac{2\bar{c}(\alpha-\bar{c})}{3\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}\alpha}\right)\\
p_B^r &= I\frac{c_B}{\bar{c}} + \frac{2\bar{c}\beta_A\beta_B}{3\alpha(1-\lambda)(\beta_A-\beta_B)}\left(1+\frac{2\bar{c}(\alpha-\bar{c})}{3\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}\alpha}\right)
\end{aligned}
\tag{18}
$$

We define $\bar{\beta} \equiv \beta_A\lambda + \beta_B(1-\lambda)$ as average preference for a good match in the population. The first term of the regulator's reimbursement scheme is a pure cost partitioning that split the available budget between groups according to the group specific costs in relation to the average population costs, i.e. $I \cdot c_i/\bar{c}$. Thus, the regulator's reimbursement scheme differs from a simple cost partitioning scheme that would make group A as profitable as group B.[24] Considering a naïve regulator that would apply a simple cost partitioning scheme yields specialization positions for hospital 0 at $s_0^{\tilde{r}} = -1/4$ and for hospital 1 at $s_0^{\tilde{r}} = 5/4$ and a distance of 3/2 between the hospitals. Since 3/2 is the distance that is optimal if groups do not differ either in preference for a good match or in the price cost ratios, a pure cost partitioning scheme is only sufficient in these cases. The second term in equation (18) relies on cases where groups differ in preferences and price cost ratios. In particular, a higher treatment price than under pure cost partitioning is assigned to the group endowed with the higher preference for a good match since $\alpha - \bar{c} \geq 0$ is assumed. The group with a lower preference for a good match receives a lower treatment price than under pure cost partitioning. As demonstrated in section 4, this reimbursement scheme induces a shorter distance between the hospitals' specializations than making the group endowed with the lower preference for a good match more attractive for hospitals. To focus on the distance under regulation in greater detail, we insert the regulator's treatment prices, equation (18), in the optimal distance of specializations, equation (13).

$$
\Delta^r = s_1^r - s_0^r = \frac{1}{2} - \frac{2\bar{c}(\alpha-\bar{c})}{3\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}} \tag{19}
$$

[24] The reimbursement scheme $p_i^{\tilde{r}} = (I \cdot c_i)/\bar{c}$ fulfills the budget restriction since this reimbursement scheme is a special case of equation (18).

The regulator induces the first best distance of $\Delta^{fb} = 1/2$ if and only if the marginal utility of quality equals the marginal costs of quality, i.e. $\alpha - \bar{c} = 0$. In general, this does not hold. Since $\alpha - \bar{c} \geq 0$ is assumed, the distance under regulation between the two hospitals is always equal or smaller than the first best distance. Thus, the regulator approves a deviation from the first best specializations to implement a higher quality level induced by fiercer quality competition. Since the distance in equation (19) is independent of the budget, I, the budget could be consumed by either quality or the hospitals' profits. Inserting the price scheme and the specialization positions under regulation in the Nash equilibrium for qualities, equation (6), we derive the optimal quality under price regulation. Due to symmetry, both hospitals provide the same level of quality. For the sake of clarity, we rearrange the regulator induced quality by using the regulator induced specialization distance, Δ^r, that is defined as in equation (19) and, thus, depends on exogenous parameters only.

$$q^r = \frac{I}{\bar{c}} - \frac{\bar{c}}{\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)}\left(\frac{2}{3} - \Delta^r + \frac{4\bar{c}(\alpha - \bar{c})}{9\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}}\right) \tag{20}$$

The first term of the regulator induced quality, $I/\bar{c}$, equals the first best quality. Since the regulator induces a specialization equal to or smaller than 1/2 the second term is negative. Even if the regulator implements the first best specializations associated with a distance of 1/2, the first best quality is not implemented. If Δ^r is replaced by equation (19), we can rearrange the regulator induced quality.

$$q^r = \frac{I}{\bar{c}} - \frac{\bar{c}}{3\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)}\left(\frac{7}{2} - \frac{2\bar{c}(\alpha - \bar{c})}{3\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}}\right) \tag{21}$$

It is straightforward to verify that the regulator induced quality in equation (21) exceeds the quality a naïve regulator would implement, i.e. $q^{\tilde{r}} = \frac{I}{\bar{c}} - \frac{3\bar{c}}{2\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)}$, who set treatment prices according to a pure cost partitioning.

Finally, we investigate the effect of the regulation on the hospital profits by inserting the treatment prices, qualities and specializations under regulation in the profit function equation (4).

$$\pi^r = \frac{\bar{c}^2}{6\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)}\left(\frac{2}{3}-\Delta^r+\frac{4\bar{c}(\alpha-\bar{c})}{9\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)\bar{\beta}}\right) \tag{22}$$

Again, Δ^r is defined as in equation (19) and, as already discussed, Δ^r is shorter than or equal to 1/2. Even if the first best specialization distance is implemented the hospitals' profits are positive. Thus, if the regulator is only able to determine the reimbursement scheme, neither the first best quality nor the first best specializations can be achieved. Consequently, the hospitals' profits are positive since zero profits are connected with the first best solution. Similar to equation (19), the profits implemented by regulation are independent of the budget I. Therefore, the health care budget is completely consumed by quality since quality depends on the budget. Adjusting the health care sector specific budget, each quality level can be realized except for the first best quality level since it depends on the budget itself.

6. Conclusion

In a Hotelling-model with two patient groups that differ in preferences and in treatment cost, we analyzed hospital competition and optimal regulation policy. Hospitals use two instruments, quality and specialization, to attract patients. Treatment prices are set by a regulator and, thus, hospitals are price takers. Our model extends the related literature since we combine two different patient groups with a Hotelling-model of endogenous horizontal and vertical differentiation.

We find a Nash-equilibrium in quality that implies fiercer quality competition if hospitals choose to locate near the center of the patients' distribution and less quality competition if the specialization positions deviate from the center of the patient's distribution. We derive a symmetric specialization equilibrium that induces the same level of quality for both hospitals. The actual specialization locations depend mainly on two relations, i.e. which group is more profitable for hospitals and which group is endowed with the higher preference for a good match. Since we relax the assumption that the specialization strategy set is equivalent to the [0,1]-interval, we infer that a necessary yet not sufficient condition for specialization positions inside the patient interval is that the more profitable group is endowed with a higher preference for a good match. Otherwise, the specializations always locate outside the patient interval ("over-specialization").

Introducing a regulator that sets prices according to a social welfare function, we derived a price scheme that deviates from a pure cost proportioning scheme. The regulator takes advantage of the heterogeneity in groups by assigning a price higher as under pure cost reimbursement to the group that is more responsible to specialization differentiation which induces hospitals to locate closer to each other and result in fiercer quality competition. Although the regulator cannot induce the first best in quality and specialization that maximizes the social welfare function, it is able to generate a higher quality and a better specialization match than a regulator that chooses prices according to a pure cost partitioning. This finding correspond to result in Brekke et al. (2006) and Bardey et al. (2012) where a regulator is not able to implement the first best if it can only set treatment prices.

Our model shows that existing differences in groups influence hospitals behavior and should be considered by a price scheme that regulates treatment prices. Accounting for differences in groups can improve the pure cost proportioning reimbursement system that corresponds to the DRGs System and induce higher quality. In particular, the group's preferences are important factors to determine the quality and specialization allocations as well as the optimal price scheme under regulation. Future research should investigate how patients that suffer from different complex diseases weight their preferences for quality and specialization to clarify this relationship.

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Appendix

A.1 Reaction functions

The reaction function of resulting from the First order condition in equation (5) are as follows.

$$q_0(q_1) = \frac{\frac{1}{2}\left(\frac{p_A\lambda}{\beta_A} + \frac{p_B(1-\lambda)}{\beta_B}\right)}{\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)} + \frac{1}{2}q_1 - \frac{\frac{1}{2}(s_1^2 - s_0^2)\big(c_A\lambda + c_B(1-\lambda)\big)}{\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)}$$

$$q_1(q_0) = \frac{\frac{1}{2}\left(\frac{p_A\lambda}{\beta_A} + \frac{p_B(1-\lambda)}{\beta_B}\right)}{\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)} + \frac{1}{2}q_0 - \frac{\left[\frac{1}{2}(s_1^2 - s_0^2) + (s_1 - s_0)\right]\big(c_A\lambda + c_B(1-\lambda)\big)}{\alpha\left(\frac{c_A\lambda}{\beta_A} + \frac{c_B(1-\lambda)}{\beta_B}\right)}$$

A.2 Effect of the preference for a good match on the optimal quality

To derive the influence of the preference for a good match on the optimal quality, we apply the implicit function theorem on the first order condition, equation (5), with respect to β_i. For this purpose, both first order conditions, regarding hospital 0 and hopsital 1, have to be considered since the optimal quality of hospital 0 depends on the quality choice of hospital 1 and vice versa.[25]

$$\begin{bmatrix} \left.\frac{dq_0}{d\beta_i}\right|_{q_0=q_0^*, q_1=q_1^*} \\ \left.\frac{dq_1}{d\beta_i}\right|_{q_0=q_0^*, q_1=q_1^*} \end{bmatrix} = -\begin{bmatrix} \frac{\partial^2\pi_0}{(\partial q_0)^2} & \frac{\partial^2\pi_0}{\partial q_0 \partial q_1} \\ \frac{\partial^2\pi_1}{\partial q_1 \partial q_0} & \frac{\partial^2\pi_1}{(\partial q_1)^2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \frac{\partial^2\pi_0}{\partial q_0 \partial\beta_i} \\ \frac{\partial^2\pi_1}{\partial q_1 \partial\beta_i} \end{bmatrix}$$

To rearrange this expression, we define $SOC \equiv \partial^2\pi_0/(\partial q_0)^2 = \partial^2\pi_1/(\partial q_1)^2$ and use the slope of the reaction functions, equation (8). Furthermore, one can easily varify that $\partial^2\pi_0/(\partial q_0 \partial q_1) = \partial^2\pi_1/(\partial q_1 \partial q_0) = -SOC/2$ has to hold which we use, in addition, to optain the following equation.

$$\left.\frac{dq_0}{d\beta_i}\right|_{q_0=q_0^*, q_1=q_1^*} = -\frac{\frac{\partial^2\pi_0}{\partial q_0 \partial\beta_i} + \frac{\partial^2\pi_1}{\partial q_1 \partial\beta_i} \cdot \frac{dq_0}{dq_1}}{\frac{3}{4}SOC}$$

[25] See Mas-Colell et al. (1995) for applying the implicit function theorem if more than one equation is considered.

$$\left.\frac{dq_1}{d\beta_i}\right|_{q_0=q_0^*,q_1=q_1^*} = -\frac{\frac{\partial^2\pi_1}{\partial q_1\partial\beta_i} + \frac{\partial^2\pi_0}{\partial q_0\partial\beta_i}\cdot\frac{dq_1}{dq_0}}{\frac{3}{4}SOC}$$

A.3 Second order conditions regarding specialization

The second order conditions regarding the specialization equilibrium are as follows.

$$\frac{\partial^2\pi_0(q_0^*,q_1^*,s_0,s_1)}{(\partial s_0)^2} = -\frac{\bar{c}^2(3s_0+s_1+4)}{9\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)}$$
$$\frac{\partial^2\pi_1(q_0^*,q_1^*,s_0,s_1)}{(\partial s_1)^2} = \frac{\bar{c}^2(s_0+3s_1-8)}{9\alpha\left(\frac{c_A\lambda}{\beta_A}+\frac{c_B(1-\lambda)}{\beta_B}\right)}$$

To guarantee non-positive second order conditions, both conditions, $3s_0+s_1+4\geq 0$ and $s_0+3\,s_1-8\leq 0$, have to be fulfilled. For symmetric specializations, i.e. $s_0+s_1=1$, the two conditions simplify to $s_0\geq -2.5$ and $s_1\leq 3.5$.

A.4 Effect of specialization on the optimal quality

The implicit function theorem with respect to the rival's specialization choice is applied to the first order condition, equation (5). As in Appendix A.2 it is necessary to consider that both first order conditions establish the Nash equilibrium to obtain the derivative since the rival's specialization choice affect the hospital's quality choice as well as the rival's quality choice.

$$\begin{bmatrix}\left.\frac{dq_j}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*}\\ \left.\frac{dq_{-j}}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*}\end{bmatrix} = -\begin{bmatrix}\frac{\partial^2\pi_j}{\left(\partial q_j\right)^2} & \frac{\partial^2\pi_j}{\partial q_j\partial q_{-j}}\\ \frac{\partial^2\pi_{-j}}{\partial q_{-j}\partial q_j} & \frac{\partial^2\pi_{-j}}{\left(\partial q_{-j}\right)^2}\end{bmatrix}^{-1}\cdot\begin{bmatrix}\frac{\partial^2\pi_j}{\partial q_j\partial s_{-j}}\\ \frac{\partial^2\pi_{-j}}{\partial q_{-j}\partial s_{-j}}\end{bmatrix}$$

Rearranging the expression, we obtain the following equation where we use $SOC\ \equiv \partial^2\pi_j/\left(\partial q_j\right)^2 = \partial^2\pi_{j-1}/\left(\partial q_{j-1}\right)^2$.

$$\left.\frac{dq_j}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*} = -\frac{SOC\cdot\frac{\partial^2\pi_j}{\partial q_j\partial s_{-j}} - \frac{\partial^2\pi_j}{\partial q_j\partial q_{-j}}\cdot\frac{\partial^2\pi_{-j}}{\partial q_{-j}\partial s_{-j}}}{SOC^2 - \frac{\partial^2\pi_j}{\partial q_j\partial q_{-j}}\cdot\frac{\partial^2\pi_{-j}}{\partial q_{-j}\partial q_j}}$$

$$\left.\frac{dq_{-j}}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*} = -\frac{SOC \cdot \frac{\partial^2 \pi_{-j}}{\partial q_{-j}\partial s_{-j}} - \frac{\partial^2 \pi_{-j}}{\partial q_{-j}\partial q_j} \cdot \frac{\partial^2 \pi_j}{\partial q_j \partial s_{-j}}}{SOC^2 - \frac{\partial^2 \pi_j}{\partial q_j \partial q_{-j}} \cdot \frac{\partial^2 \pi_{-j}}{\partial q_{-j}\partial q_j}}$$

We use the slope of the reaction functions, equation (8), and exploit that $\partial^2\pi_0/(\partial q_0 \partial q_1) = \partial^2\pi_1/(\partial q_1 \partial q_0) = -SOC/2$ has to hold to optain the following derivatives.

$$\left.\frac{dq_j}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*} = -\frac{\frac{\partial^2 \pi_j}{\partial q_j \partial s_{-j}} + \frac{\partial^2 \pi_{-j}}{\partial q_{-j}\partial s_{-j}} \cdot \frac{dq_j}{dq_{-j}}}{\frac{3}{4}SOC}$$

$$\left.\frac{dq_{-j}}{ds_{-j}}\right|_{q_j=q_j^*,q_{-j}=q_{-j}^*} = -\frac{\frac{\partial^2 \pi_{-j}}{\partial q_{-j}\partial s_{-j}} + \frac{\partial^2 \pi_j}{\partial q_j \partial s_{-j}} \cdot \frac{dq_{-j}}{dq_j}}{\frac{3}{4}SOC}$$