Optimal exploitation of renewable resource stocks: Necessary conditions

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Summary

We study a model for the exploitation of renewable stocks developed in [4]. In this particular control problem, the control law contains a measurable and an impulsive control component. We formulate Pontryagin’s maximum principle for this kind of control problems, proving first order necessary conditions of optimality. Manipulating the correspondent Lagrange multipliers we are able to define two special switch functions, that allow us to describe the optimal trajectories and control policies nearly completely for all possible initial conditions in the phase plane.

Keywords: Optimal control, Fishery management, Impulsive control, Maximum principle
1 Introduction

1.1 Description of the model
Consider a bio-economic model of the commercial fishery under sole ownership. The model is governed by the quantities described in Table 1.

| $t$ | time variable |
|-----|---------------|
| $x(t)$ | population biomass at time $t$ |
| $h(t)$ | harvest rate at time $t$ |
| $E(t)$ | fishing effort at time $t$ |
| $K(t)$ | amount of capital invested in the fishery at time $t$ |
| $I(t)$ | investment rate at time $t$ |

Table 1: Main relevant variables.

The model is based on the following assumptions:

- $h(t) = qE(t)x(t)$; $q$ is a catch coefficient;
- $x'(t) = F(x(t)) - qE(t)x(t)$, $t \geq 0$, $x(0) = x_0$; $F$ is the natural growth function;
- $K'(t) = -\gamma K(t) + I(t)$, $t \geq 0$, $K(0) = K_0$; $\gamma \geq 0$ is the rate of depreciation;
- constraints: $0 \leq x(t)$, $K(t)$, $E(t)$; $E(t) \leq K(t)$;
- non-malleability: $0 \leq I(t) \leq \infty$, $t \geq 0$;
- existence of two biological equilibrium points: $F(0) = F(\bar{x}) = 0$, $\bar{x} > 0$;
- properties of the production function: $F \in C^2[0, \infty)$, $F(x) > 0$, $0 < x < \bar{x}$, $F''(x) < 0$, $0 \leq x \leq \bar{x}$;
- objective function (discounted cash flow): $\int_0^\infty e^{-\delta t} \{ph(t) - cE(t) - rI(t)\} dt$; $\delta > 0$ is the instantaneous rate of discount, $p \geq 0$ is the price of landed fish, $c \geq 0$ is the operating cost per unit effort, $r \geq 0$ is the price of capital.

A concrete production function satisfying the assumption above is given by the logistic mapping $F(x) := ax(1 - \frac{x}{K})$ (with $a > 0$, $k > 0$). In our figures we use this production function.

1.2 The optimal control problem
We set $E = uK$ and consider $u$ as a second control variable. Without loss of generality we use $q = 1$. After this manipulation, the problem we want to consider is the following optimal control problem:

$$ Q(x_0, K_0) \begin{cases} 
\text{Minimize } J(x_0, K_0; I, u) := \int_0^\infty e^{-\delta t} \{rI(t) + cu(t)K(t) - pu(t)K(t)x(t)\} dt \\
\text{subject to } \\
x' = F(x) - u(t)K(t)x , t \geq 0 , x(0) = x_0 , \\
K' = -\gamma K + I(t) , t \geq 0 , K(0) = K_0 , \\
0 \leq x(t) , K(t) , 0 \leq u(t) \leq 1 , I(t) \geq 0 , t \in [0, \infty) . 
\end{cases} $$
This problem is considered in [3] along the „royal road“of Carathéodory. But the analysis is not rigorous in the details (see Section 1.3). In [9] the problem is given as an illustration for the problem of the type considered in the paper but the results are not applicable (for proving existence).

In [16] there is also a hint to this problem and finally, we find the problem in [3] considered as an example for the application of the maximum principle, but nothing has been made rigorous. For the background in fishery management see [6], [1] and [12].

It is known, see e.g. [9], that control problems may have no solution if the control variable is unbounded and both the cost functional and the dynamics depend linearly on the control. This situation is given here with respect to the control $I$. In order to avoid non–existence we have to replace the conventional control $I$ by an impulse control, i.e. jumps in the state are allowed. Therefore, we consider $I$ as a Borel measure and the capital function $K$ as a function of bounded variation. Then, problem $Q(x_0, K_0)$ becomes:

$$
P(x_0, K_0) = \begin{cases} 
\text{Minimize } J(x_0, K_0; u) := \int_0^\infty e^{-\delta t} r\mu(dt) + \int_0^\infty e^{-\delta t} \{c - px(t)\} u(t) K(t)dt \\
\text{subject to } (u, \mu) \in U_{ad} \times C^* \text{ and } \\
x' = F(x) - u(t)Kx, \; x(0) = x_0, \\
dK = -\gamma Kdt + \mu(dt), \; K(0) = K_0. 
\end{cases}
$$

Here

$$
U_{ad} := \{v \in L_\infty[0, \infty) \mid 0 \leq v(t) \leq 1 \text{ a.e. in } [0, \infty)\} \\
C^* := \{\mu | \mu \text{ a non–negative Borel measure on } [0, \infty)\}.
$$

Notice that the constraints $0 \leq x(t), K(t), \; t \in [0, \infty)$, are satisfied due to the assumptions above if $x_0 \geq 0, \; K_0 \geq 0$.

The initial value problem

$$
dK = -\gamma Kdt + \mu(dt), \; K(0) = K_0 \quad (1)
$$

has to be considered as differential equation with a measure: a function $K : [0, t_1) \rightarrow IR$ ($t_1 \in (0, \infty]$) is a solution if

$$
K(t) = K_0 - \int_0^t \gamma K(s)ds + \int_{[0, t]} \mu(ds), \; 0 \leq t < t_1; \quad (2)
$$

This implies that $K$ is right continuous in $(0, t_1)$ and $K(0) = K_{0,+}(\{t_1\})$ where $K_{0,+}$ denotes $\lim_{t \downarrow 0} K(t)$.

**Remark 1** Due to the fact that the coefficients in front of the control measure $\mu$ does not depend on the state we may use the solution concept as given above, the so called Young solutions (see [10]). Otherwise we would have to use the concept of robust solutions considered in [13], [7], [3], [14], [2]. □

We set $\kappa := \delta + \gamma, \; r' := r\kappa, \; c_* := c + r'$ and define functions $g, \psi, \psi_*$ on $(0, \bar{x})$ by

$$
g(x) := \delta - F'(x) + \frac{F(x)}{x}, \\
\psi(x) := (px - c)(\delta - F'(x)) - \frac{cF(x)}{x}, \\
\psi_*(x) := (px - c_*)(\delta - F'(x)) - \frac{c_*F(x)}{x}.
$$

Further we consider the following conditions:
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(V1) \( F \in C^2[0, \infty) \cap C^3(0, \bar{x}) \); \[ F(0) = F(\bar{x}) = 0; \quad F(x) > 0, \quad 0 < x < \bar{x}; \quad F''(x) < 0, \quad 0 \leq x \leq \bar{x}. \]

(V2) \( \delta > 0, \quad r > 0, \quad c > 0, \quad \gamma > 0. \)

(V3) \( c_\ast - p\bar{x} < 0. \)

(V4) There exist \( \bar{x}, \; x^* \in (0, \bar{x}) \) with
\[
\psi(x) < 0, \quad 0 < x < \bar{x}, \quad \psi(\bar{x}) = 0, \quad \psi(x) > 0, \; \bar{x} < x < \bar{x},
\]
\[
\psi_\ast(x) < 0, \quad 0 < x < x^*, \quad \psi_\ast(x^*) = 0, \quad \psi_\ast(x) > 0, \; x^* < x < \bar{x}.
\]

(V5) \( \psi'(x) > 0, \; x \in (0, \bar{x}), \quad \psi_\ast'(x) > 0, \; x \in (\bar{x}, \bar{x}). \)

(V6) \( g'(x) > 0, \; x \in (0, \bar{x}). \)

Remark 2 Notice that the conditions (V1), \ldots, (V6) are satisfied for the logistic production function if the constants are chosen appropriately. Notice too that (V4), (V5) contain redundant information. \( \square \)

Remark 3 In the subsequent analysis it is very important that \( x = \bar{x} \) is an attracting equilibrium point, while \( x = 0 \) is an unstable equilibrium point. \( \square \)

At this point we define \( \bar{K} := F(\bar{x})/\bar{x} \) and \( K^\ast := F(x^*)/x^\ast \). Due to assumption (V1), follows \( g(x) > 0 \) in \([0, \bar{x}]\). Therefore, we have \( \psi(x) > \psi_\ast(x) \) and, consequently, \( \bar{x} < x^\ast, \; \bar{K} > K^\ast \) must hold.

Under the assumptions (V1), \ldots, (V6) one can prove existence of optimal solutions of \( P(x_0, K_0) \); see, e.g., [13]

1.3 The verification approach

As already mentioned the problem \( P(x_0, K_0) \) is considered in [1]. By using a Hamilton–Jacobi–Bellman equation on \((0, \bar{x}) \times (0, \infty)\) a candidate for an optimal control policy is defined for each \((x_0, K_0) \in (0, \bar{x}) \times (0, \infty)\). This results in the definition of a function
\[
S : (0, \bar{x}) \times (0, \infty) \rightarrow \mathbb{R},
\]
such that for all \((x, K) \in (0, \bar{x}) \times (0, \infty)\), for all \( u \in [0, 1] \) and for all \( I \geq 0 \) – controls with jumps are avoided by considering them as „limits“ of regular controls –
\[
\delta S(x, K) + F(x)S_x(x, K) - \gamma KS_K(x, K) \geq I(S_K(x, K) + r) + uK\{qxS_x(x, K) - pqx + c\} \tag{3}
\]
holds. Then it is stated that \( S \) is the value function \( V \) where the value function \( V \) is given here by
\[
V(x_0, K_0) := \inf \{ J(x_0, K_0; I, u) | (I, u) \text{ admissible} \}, \quad (x_0, K_0) \in (0, \bar{x}) \times (0, \infty).
\]
Implicitly there are only used controls which result in states \( x, K \) such that
\[
\int_{t \to \infty} e^{-\delta t} S(x(t), K(t)) = 0.
\]
One can follow the analysis in [4] partly but for some steps the assumptions are not sufficient and some arguments are not complete. Since $S$ is not differentiable everywhere they use the argument that each problem $P(x_0, K_0)$ may be approximated by the problem $Q(x_0, K_0)$. This density argument is a very deep topological argument and no results to make this argument rigorous are available from the literature. It is open whether on this road the verification of optimal controls is possible. Thus, the verification of the optimal policy in [4] has to be considered as an open problem. Two different ways may be considered in order to circumvent these difficulties: Firstly, extension of the so-called Hamilton–Jacobi–Bellman equation such that jumps are allowed. Secondly, proof of the closure property inherent in the density argument.

1.4 Outline of the paper

In Section 2 we study the necessary conditions, furnished by a special version of Pontryagin’s maximum principle (see Appendix). Through manipulation of the Lagrange multipliers we manage to define two special switch functions. The first switch helps to determine the bang-bang behavior of the measurable component of the control policy, while the second one is a jump switch, which gives us a necessary condition for discontinuities in the state variables.

In Section 3 we use the necessary conditions of optimality, rewritten for the switch functions, in order to detect both optimal and non optimal behavior of the admissible processes. Following trajectories backwards in time and observing the evolution of the switches, we are able to construct auxiliary curves in the phase plane $(x, K)$, that are very useful to determine optimal behavior. Particularly we are able to detect two jump curves in the phase plane. This shows that the application of the Pontryagin maximum principle can be used in order to construct the extremals of the problem.

In Section 4 we put all arguments together and summarize the obtained results in the form of Theorem 27. The next two theorems, 28 and 29, treat some special initial conditions, which may occur. However, the argumentation follow the spirit of Theorem 27.

It is worth to mention that our results are in agreement with the conclusions in [4].

1.5 Interpretation of the main results

In this section we provide the economic interpretation of our main result, which is obtained in Theorem 27 and auxiliary Theorems 28 and 29. These theorems describe optimal behavior of processes and corresponding Lagrange multipliers for all initial conditions in the state space $[0, \bar{x}] \times [0, \infty)$.

For details on the notation, particularly the definition of the curves $\Sigma^*$, $\tilde{\Sigma}$, $\Sigma_4$, $\Sigma_0$, $\Gamma_1$, $\Gamma_2$, $\Gamma_3$, $\Gamma_4$, the reader should refer to Section 3 (see also to Figure 3). The main regions (R1), . . . , (R5) are defined in Section 4 and are illustrated in Figure 4.

Case 1: $(x_0, K_0) = (x^*, K^*)$

One should invest with constant rate ($\mu = \gamma K^* dt$) and fish with maximal effort ($u = 1$) for all $t \geq 0$. Consequently, the optimal trajectory satisfies $(x(t), K(t)) = (x^*, K^*)$ for all $t \geq 0$ (this is the first singular arc).

Case 2: $(x_0, K_0) \in \Sigma^*$

At the initial time $t = 0$ one should make an impulsive investment, in such a way that $(x_0, K_{0+}) = (x^*, K^*)$. Then one should proceed as in Case 1.

Case 3: $(x_0, K_0) \in (R2)$
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One should not invest \((\mu = 0)\) and fish with maximal effort \((u = 1)\) until the optimal trajectory reaches the curve \(\Sigma^*\). Then one should proceed as in Case 2.

Case 4: \((x_0, K_0) \in (R1)\)
At the initial time \(t = 0\) one should make an impulsive investment, in such a way that \((x_0, K_{0,+}) \in \Sigma_s\), the so called \textit{jump curve}. Then one should proceed as in Case 3.

Case 5: \((x_0, K_0) \in (R3)\)
One should not invest \((\mu = 0)\) and should not fish \((u = 0)\) until the optimal trajectory reaches the curve \(\Sigma_0\) (this configures \((R3)\) as a \textit{moratorium region}). Then one should proceed as in Case 3.

Case 6: \((x_0, K_0) \in \tilde{\Sigma}\)
One should not invest \((\mu = 0)\) and should fish with moderate effort \(u(t) = K(t)^{-1}F(\bar{x})\bar{x}^{-1}\) until the optimal trajectory reaches the state \((\bar{x}, \bar{K})\) (second singular arc). Note that the fish population remains constant \((x = \bar{x})\) during this first time interval. Then one should proceed as in Case 3.

Case 7: \((x_0, K_0) \in (R4)\)
One should not invest \((\mu = 0)\) and should not fish \((u = 0)\) until the optimal trajectory reaches the curve \(\tilde{\Sigma}\) (this configures \((R4)\) as a \textit{moratorium region}). Then one should proceed as in Case 6.

Case 8: \((x_0, K_0) \in (R5)\)
One should not invest \((\mu = 0)\) and should fish with maximal effort \((u = 1)\) until the optimal trajectory reaches the curve \(\tilde{\Sigma}\). Then one should proceed as in Case 6.

Case 9: \((x_0, K_0) \in \Sigma_0 \cup \Sigma_s \cup \Gamma_3\)
This case is analog to Case 3.

Case 10: \((x_0, K_0) \in \Gamma_4\)
This case is analog to Case 7.

2 Necessary conditions

In this section we use the maximum principle to derive first order necessary conditions for problem \(P(x_0, K_0)\) and define, with the aid of the Lagrange multipliers, two auxiliary functions (switches) that play a key rule in the analysis of the optimal trajectories. We start defining the Hamilton function \(\tilde{H}\) by

\[
\tilde{H}(t, \bar{x}, \bar{K}, w, \tilde{\lambda}_1, \tilde{\lambda}_2, \eta) := \tilde{\lambda}_1(F(\bar{x}) - w\bar{K}\bar{x}) - \tilde{\lambda}_2\gamma\bar{K} - \eta e^{-\delta t}(c - p\bar{x})w\bar{K}.
\]

Let \((u, \mu)\) be an optimal control policy for \(P(x_0, K_0)\) and let \((x, K)\) be the associated state. From the maximum principle in the appendix we obtain constants \(\tilde{\lambda}_{1,0}, \tilde{\lambda}_{2,0}, \eta \in \mathbb{R}\) and adjoint
functions $\tilde{\lambda}_1, \tilde{\lambda}_2 : [0, \infty) \rightarrow \mathbb{R}$ such that

$$\tilde{\lambda}^2_{1,0} + \tilde{\lambda}^2_{2,0} + \eta^2 \neq 0, \; \eta \geq 0,$$

$$x' = F(x) - u(t)Kx, \; x(0) = x_0,$$

$$dK = -\gamma K dt + \mu(dt), \; K(0) = K_0,$$

$$\tilde{\lambda}'_1 = -\tilde{\lambda}_1 F'(x) - u(t)K + \eta e^{-\delta t}pu(t)K, \; \tilde{\lambda}_1(0) = \tilde{\lambda}_{1,0},$$

$$\tilde{\lambda}'_2 = \tilde{\lambda}_1 xu + \gamma \tilde{\lambda}_2 + \eta e^{-\delta t} (c - px)u(t), \; \tilde{\lambda}_2(0) = \tilde{\lambda}_{2,0},$$

$$\tilde{\lambda}_2(t) - \eta e^{-\delta t} \tau \leq 0 \text{ for all } t \in [0, \infty),$$

$$\tilde{\lambda}_2(t) - \eta e^{-\delta t} \tau = 0 \mu-a.e. \text{ in } [0, \infty),$$

$$H(t, x(t), K(t), u(t), \tilde{\lambda}_1(t), \tilde{\lambda}_2(t), \eta) = \max_{w \in [0,1]} \tilde{H}(t, x(t), K(t), w, \tilde{\lambda}_1(t), \tilde{\lambda}_2(t), \eta) \text{ a.e. in } [0, \infty).$$

Now we set

$$\lambda_1(t) := \tilde{\lambda}_1 e^{\delta t}, \; \lambda_2(t) := \tilde{\lambda}_2 e^{\delta t}, \; \lambda_{1,0} := \lambda_1(0), \; \lambda_{2,0} := \lambda_2(0),$$

$$H(t, x, \dot{K}, w, \lambda, \eta) := (-\lambda x + \eta (px - c)) \dot{K} w.$$

Next we define the auxiliary functions $z, \lambda : [0, \infty) \rightarrow \mathbb{R}$

$$z := -\lambda_1 x + \eta (px - c), \; \lambda := \lambda_2, \; z_0 := \lambda_{1,0}, \; \lambda_0 := \lambda_{2,0}.$$

that are used to reinterpret the necessary conditions. We call $z$ and $\lambda$ switch variables. Note that $z$ defines along the maximum condition the value of $u(t)$, namely $u(t) = 0$ if $z(t) < 0$ and $u(t) = 1$ if $z(t) > 0$. If $z(t)$ vanishes, then the value of $u(t)$ has to be determined by other means. The function $\lambda$ defines a jump switch, since $\mu(\{t\}) > 0$ for some $t \in [0, \infty)$ implies $\lambda(t) = \eta r$.

Finally we are able to rewrite the necessary optimality conditions in the form

$$z_0^2 + \lambda_0^2 + \eta^2 \neq 0, \; \eta \geq 0,$$

$$x' = F(x) - u(t)Kx, \; x(0) = x_0,$$

$$dK = -\gamma K dt + \mu(dt), \; K(0) = K_0,$$

$$z' = zg(x) - \eta \psi(x), \; z(0) = z_0,$$

$$\lambda' = \kappa \lambda - z u(t), \; \lambda(0) = \lambda_0,$$

$$\lambda(t) - \eta r \leq 0 \text{ for all } t \in [0, \infty),$$

$$\lambda(t) - \eta r = 0 \mu-a.e. \text{ in } [0, \infty),$$

$$z(t)K(t)u(t) = \max_{w \in [0,1]} z(t)K(t)w \text{ a.e. in } [0, \infty).$$

We want to exclude the irregular case $\eta = 0$. This is prepared by

**Lemma 4** A policy $(u, \mu)$ such that there exists $\tau > 0$ with $\mu(A) = 0$ for each measurable subset $A$ of $(\tau, \infty)$ is not optimal for each $(x_0, K_0) \in (0, \bar{x}) \times (0, \infty)$.

**Proof:** Suppose $(u, \mu)$ is a policy with the property that for each $\tau > 0$ we have $\mu(A) = 0$ for all $A \subset (\tau, \infty)$. Then we have for the resulting trajectory $(x, K)$: $\lim_{\tau \to \infty} x(t) = \bar{x}$, $\lim_{\tau \to \infty} K(t) = 0$. Therefore it is enough, due to Belman’s principle of optimality, to show that such a trajectory for initial data $(x_0, K_0)$ in a neighborhood of $(\bar{x}, 0)$ cannot be optimal.
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We choose \( \alpha > 0 \) and \( x_1 \in (x^*, \bar{x}) \) with \( c_\alpha - px \leq -\alpha \) for \( x \in [x_1, \bar{x}] \); this is possible due to the assumption (V3). Let \( n \in \mathbb{N} \) be with \(-n\alpha + p\bar{x} < 0\) and set \( K_1 := F(x_1)/x_1 \).

Let \((x, K)\) be the trajectory associated with \((u, \mu)\), i.e.
\[
x'(t) = F(x(t)) - u(t)K_0e^{-\gamma t}x(t), \quad t > 0, \quad x(0) = x_0,
\]
where \( x_0 \geq x_1, K_0 \in (0, K_1/(n + 1)) \). We are able to describe a better policy \((\bar{x}, \bar{K}, \bar{u}, \bar{\mu})\), namely:
\[
\bar{x}'(t) = F(\bar{x}(t)) - \bar{u}(t)\bar{K}\bar{x}(t), \quad \bar{x}(0) = x_0, \quad d\bar{K}(t) = -\gamma \bar{K} + \bar{\mu}(dt), \quad \bar{K}(0) = K_0,
\]
where \( \bar{u} \equiv 1 \) and \( \bar{\mu} \) describes a jump at time \( t = 0 \) of height \( h \). Notice that we have \( \bar{x}(t) \geq x_1, (K_0 + h)e^{-\gamma t} \leq K_1 \) for all \( t \geq 0 \). We compare the values of the objective function:
\[
rh + \int_0^\infty e^{-\delta t}(c - p\bar{x}(t))(K_0 + h)dt - \int_0^\infty e^{-\delta t}(c - px(t))u(t)K_0e^{-\gamma t}dt
\]
\[
\leq rh + \int_0^\infty e^{-\delta t}(c - p\bar{x}(t))(K_0 + h)dt - \int_0^\infty e^{-\delta t}(c - px(t))K_0dt
\]
\[
= rh + \int_0^\infty e^{-\delta t}(c - p\bar{x}(t))(K_0 + h)dt - \int_0^\infty e^{-\delta t}(c - px(t))K_0dt
\]
\[
+ \int_0^\infty e^{-(\delta + \gamma)t}(c - p\bar{x}(t))K_0dt - \int_0^\infty e^{-(\delta + \gamma)t}(c - px(t))K_0dt
\]
\[
= h \int_0^\infty e^{-(\delta + \gamma)t} \bar{x}' dt + h \int_0^\infty e^{-(\delta + \gamma)t}(c - p\bar{x}(t))dt + K_0h \int_0^\infty e^{-(\delta + \gamma)t}(x(t) - \bar{x}(t))dt
\]
\[
\leq -\alpha(\delta + \gamma)^{-1} + K_0p\bar{x}(\delta + \gamma)^{-1} = K_0(\delta + \gamma)^{-1}(-n\alpha + p\bar{x}) < 0.
\]

\[\blacksquare\]

Corollary 5 Let \((x, K, u, \mu)\) be an optimal process with adjoint variables \( \eta, z, \lambda \). If \( \eta = 0 \), then there exists for any \( \tau > 0 \) some \( t > \tau \) with \( \lambda(t) = 0 \).

Proof: If there exists a \( \tau > 0 \) such that \( \lambda(t) < 0 \), for all \( t > \tau \), then \( \mu(A) = 0 \) for each measurable subset \( A \) of \((\tau, \infty)\). This contradicts the optimality of the policy \((u, \mu)\) (see Lemma 3), proving the corollary.

\[\blacksquare\]

Theorem 6 Let \((x, K, u, \mu)\) be an optimal process with adjoint variables \( \eta, z, \lambda \). Then \( \eta \neq 0 \).

Proof: If \( \eta = 0 \), we have the necessary conditions \( z_0^2 + \lambda_0^2 \neq 0 \),
\[
z' = zg(x), \quad z(0) = z_0,
\]
\[
\lambda' = \kappa \lambda - zu(t), \quad \lambda(0) = \lambda_0,
\]
\[
\lambda(t) \leq 0 \text{ for all } t \in [0, \infty),
\]
\[
\lambda(t) = 0 \mu\text{-a.e. in } [0, \infty).
\]

We distinguish six cases according to the initial conditions \((\lambda_0, z_0)\):

i) \( \lambda_0 = 0, \; z_0 = 0 \): Here we have \( z(t) = 0, \lambda(t) = 0 \), for all \( t > 0 \). This contradicts the necessary condition \( z_0^2 + \lambda_0^2 \neq 0 \).
\( \lambda_0 = 0, \ z_0 < 0 \): Clearly, \( \lambda'(0) = 0 \) and \( \lambda'(0) < 0 \). This implies \( z(t) < 0, \ u(t) = 0, \lambda(t) = 0 \) for all \( t > 0 \). Therefore, the policy \((u, \mu)\) is not better than \((u, \tilde{\mu})\) with \( \tilde{\mu} \equiv 0 \). From Corollary 5 we know that already this policy is not optimal.

\( \lambda_0 = 0, \ z_0 > 0 \): Note that \( \lambda'(0) > 0, \lambda'(0) < 0 \) and we have \( z(t) > 0, \ u(t) = 1, \lambda(t) < 0 \) for all \( t > 0 \). From Corollary 5 we obtain that this policy is not optimal.

\( \lambda_0 < 0, \ z_0 = 0 \): We have \( \lambda'(0) = 0, \lambda'(0) < 0 \). This implies \( z(t) = 0, \lambda(t) < 0 \) for all \( t > 0 \). From Corollary 5 follows that this policy is not optimal.

\( \lambda_0 < 0, \ z_0 < 0 \): We have \( \lambda'(0) < 0, \lambda'(0) < 0 \). This implies \( \lambda(t) < 0, \lambda(t) < 0 \) for all \( t > 0 \) and again due to Corollary 5 this policy is not optimal.

\( \lambda_0 < 0, \ z_0 > 0 \): In this case \( \lambda'(0) > 0, \lambda'(0) < 0 \) and we have \( z(t) > 0, \lambda(t) < 0 \) for all \( t > 0 \). Applying Corollary 5 we conclude that this policy is not optimal.

Therefore, in all cases we have a contradiction and the theorem is proved. \( \blacksquare \)

### 3 Exploitation of the necessary conditions

An immediate consequence of Theorem 6 is the fact that the Lagrange multiplier \( \eta \) can be chosen equal to one. In this case we have to analyze the following necessary conditions:

\[
\begin{align*}
x' &= F(x) - u(t)Kx, \quad x(0) = x_0, \\
dK &= -\gamma K dt + \mu(dt), \quad K(0) = K_0, \\
z' &= zg(x) - \psi(x), \quad z(0) = z_0, \\
\lambda' &= (\lambda - r)\kappa - zu(t) + r', \quad \lambda(0) = \lambda_0, \\
\lambda(t) &\leq r, \text{ for all } t \in [0, \infty), \\
\lambda(t) &= r, \mu \text{-a.e. in } [0, \infty), \\
z(t)K(t)u(t) &= \max_{w \in [0,1]} z(t)K(t)w \text{ a.e. in } [0, \infty].
\end{align*}
\]

The central problem in the analysis of the necessary conditions consists in finding out the initial conditions \( \lambda_0 = \lambda(0), \ z_0 = z(0) \) which are in agreement with the condition

\( (R) \quad \lambda(t) \leq r, \text{ for all } t \in [0, \infty). \)

One can easily check that if \( \lambda(\tau) = r \) for some \( \tau > 0 \), then \( \lambda'(\tau) = 0 \) and \( \lambda''(\tau) \leq 0 \). It is also clear that \( K_{0,+} \neq K_0 \) at most if we have \( \lambda(0) = r \). Knowing that it is possible to chose \( \eta = 1 \), we formulate Corollary 5 again:

**Corollary 7** Let \( (x, K, u, \mu) \) be an optimal process with adjoint variables \( z, \lambda \). Then for each \( \tau > 0 \) there exists \( t > \tau \) with \( \lambda(t) = r \).

**Proof:** See the proof for Corollary 5 \( \blacksquare \)

The rest of this section is devoted to the analysis of the relationship between the initial states \((x_0, K_0)\) and the initial conditions \((z_0, \lambda_0)\) of the adjoint variables. We prove a series of auxiliary lemmas, that will allow us in the next section to detect the optimal trajectories and correspondent policies.

**Lemma 8** Let \( (x, K, u, \mu) \) be optimal with adjoint variables \( z, \lambda \). Then there exists no \( \tau > 0 \) with \( x(\tau) > x^* \) and \( F(x(\tau)) \geq K(\tau)x(\tau) \).

**Proof:** Assume the contrary. We consider two cases separately:
3 EXPLOITATION OF THE NECESSARY CONDITIONS

i) If \( \lambda(\tau) = r \), then it follows from (R) that \( \lambda'(\tau) = 0 \). Consequently, \( z(\tau)u(\tau) = r' \) and \( z(\tau) = r' \). Now, it follows from (V4) and the assumption \( x(\tau) > x^* \) that \( \psi_+(x(\tau)) > 0 \) and substituting in the dynamic of \( z \) we have

\[
z'(\tau) = (z(\tau) - r')g(x(\tau)) - \psi_+(x(\tau)) < 0.
\]

Because of \( \lambda''(\tau) = -z'(\tau) > 0 \) we have a contradiction to (R).

ii) If \( \lambda(\tau) < r \), then we obtain from Corollary 7 a \( \tau_1 > \tau \) with \( \lambda(\tau_1) = r, \lambda(t) < r, \) for \( t \in [\tau, \tau_1) \). Observing the dynamic of the pair \( (x(t), K(t)) \), we conclude that \( 0 \leq F(x(t)) - K(t)x(t) \leq x'(t), \) \( t \geq \tau \). Then for \( t = \tau_1 \) we have \( F(x(\tau_1)) \geq K(\tau_1)x(\tau_1), x(\tau_1) \geq x(\tau) > x^* \). To obtain a contradiction, we argument as in i), setting \( \tau := \tau_1 \).

\[
\blacksquare
\]

Lemma 9 Let \( (x, K, u, \mu) \) be optimal with adjoint variables \( z, \lambda \). Then for \( x_0 = x^* \), \( K_0 > K^* \) the initial conditions \( \lambda_0 = r, z_0 = r' \) are not possible.

**Proof:** Assume that \( \lambda_0 = r, z_0 = r' \). From the differential equations for \( x, \lambda \) and \( z \) follows \( x'(0) < 0, \lambda'(0) = 0, z'(0) = 0 \). Then we have

\[
\lambda''(0) = \lambda'(0)\kappa - z'(0) = 0, \quad \lambda''(0+) = \psi_+(x^*)[F(x^*) - K_{0+}x^*] < 0.
\]

Therefore, \( \lambda(t) \neq r \) does not occur. This holds also if \( z_0 > r' \) since in this case we have \( \lambda'(0) < 0 \). Due to Corollary 7 \( \lambda(t) < r \) for all \( t > 0 \) is not possible. Let

\[
\tau := \sup\{\sigma \geq 0 \mid \lambda(t) < r, 0 < t < \tau\}.
\]

We know that \( \tau < \infty, \lambda(\tau) = r, \lambda'(\tau) = 0, z(\tau) = r' \). Since \( x_0 = x^* \) and \( x'(0) < 0 \), we have three possible cases:

i) If \( x(t) < x^* \) for all \( t \in (0, \tau) \), then \( z'(t) > 0 \), for \( t \in [0, \tau) \) and \( z(0) = z(\tau) = r' \) which is not possible.

ii) If \( x(t) > x^* \), then \( z(t) > x(t) = x^* \), then we may argument as in i).

iii) If \( x(t) > x^* \), then we can choose \( \sigma \in (0, \tau) \) with \( x(t) < x^* \), for \( t \in [0, \sigma] \), and \( x(\sigma) = x^* \). Note that \( z(t) > r' \) (and consequently \( u(t) = 1 \)) for \( t \in (0, \sigma] \). From the definition of \( \sigma \) we have \( x'(\sigma) > 0 \), i.e. \( K(\sigma) \leq F(x^*)/x^* \). Now, arguing as in case ii) in the proof of Lemma 8 we obtain the inequality \( K(\sigma) > F(x^*)/x^* \), again a contradiction.\[\blacksquare\]

Lemma 10 Let \( (x, K, u, \mu) \) be optimal with adjoint variables \( z, \lambda \). If \( x_0 = x^* \), \( K_0 = K^* \), then \( \mu = \gamma K^{*d} t \) and \( x(t) = x^* \), \( K(t) = K^* \), \( \lambda(t) = r, z(t) = r' \), \( u(t) = 1 \), for \( t \geq 0 \).

**Proof:** Assume \( \lambda_0 < r \). From Corollary 7 we obtain \( \tau > 0 \) with \( \lambda(\tau) = r, \lambda(t) < r, \) for \( t \in (0, \tau) \). Condition (R) implies \( \lambda'(\tau) = 0 \) and therefore \( z(\tau) = r' \); especially we have \( u(t) \equiv 1 \) in a neighborhood of \( t = \tau \). From \( x' = F(x) - Kx \) we obtain \( x(\tau) > x^* \) and \( \lambda''(\tau) = -z'(\tau) = \psi_+(x(\tau)) > 0 \), contradicting (R). Therefore, we must have \( \lambda_0 = r \). Next verify that \( z_0 = r' \):

i) If \( z_0 < r' \), then \( \lambda'(0) = r' - z_0 > 0 \), contradicting (R).

ii) If \( z_0 > r' \), then \( \lambda'(0) < 0 \). Arguing with Corollary 7 (see the beginning of this proof), we obtain a \( \tau > 0 \) with \( \lambda(\tau) = r, \lambda'(\tau) = 0 \) but \( \lambda''(\tau) > 0 \), again contradicting (R). Therefore, we must have \( z_0 = r' \). Now define

\[
\tau := \sup\{\sigma \geq 0 \mid \lambda(t) = r, 0 \leq t \leq \sigma\}.
\]

If \( \tau = 0 \), then \( \lambda'(0) < 0 \) and arguing as in ii) above we obtain a contradiction. Therefore, we must have \( \tau > 0 \). Note that if \( \sigma \in (0, \tau) \), then \( \lambda(t) = r, \lambda'(t) = 0, z(t) = r', z'(t) = 0 \), for

\[1\]One should note that the development in case ii) in the proof of Lemma 8 still holds if \( x(\tau) = x^* \).
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t ∈ [0, σ]. It follows ψs(x(t)) = 0, for t ∈ [0, σ], and with condition (V4) we have x(t) = x∗, for t ∈ [0, σ]. From the differential equation x′ = F(x) − Kx follows K(t)x∗ = F(x∗), for t ∈ [0, σ], and with dK = −γK dt + µ(dt) we finally obtain µ(0, σ) = −γK dt.

Clearly, it is enough to prove τ = ∞. If this were not the case, we would have either K(τ+) > K∗ or K(τ−) = K∗. Due to Lemma 9 K(τ+) > K∗ is not possible. The other case, K(τ+) = K∗, cannot be true, since otherwise we could repeat the complete argumentation for the initial time t = τ, contradicting the maximality of τ.

Lemma 11 Let (x, K, u, µ) be optimal with adjoint variables z, λ. Then for x0 = x∗, K0 ≤ K∗ we must have the initial values λ0 = r, z0 = r′, λ′(0) = 0, z′(0) = 0. Further we have K0+ = K∗.

Proof: The equality λ′(0) = 0, z′(0) = 0 follow from x0 = x∗, λ0 = r, z0 = r′ in an obvious way. Consequently, we only have to prove λ0 = r, z0 = r′.

If λ0 < r, then there exists τ > 0 such that λ(t) < r, for t ∈ [0, τ). Then K(t) < K0 ≤ K∗ for t ∈ (0, τ], and consequently x(τ) > x∗, x′(τ) = F(x(τ)) − K(t)x(τ) > 0. But this cannot occur due to Lemma 8. Therefore, λ0 = r.

If z0 < r′, then λ′(0) < 0. Arguing as before (assumption λ0 < r) we obtain a contradiction. Therefore, z0 ≥ r′. Next we exclude the case z0 > r′.

If K0 = K∗, then Lemma 10 implies z0 = r′ proving the theorem. If K0 < K∗, we consider the following cases:

i) K0+ > K∗ is not possible due to Lemma 9

ii) If K0+ = K∗, then z0 = r′ follows from Lemma 10

iii) K0+ ∈ [K0, K∗). We obtain from the dynamic of the pair (x, K) some τ > 0 with x(τ) > x∗, F(x(τ)) − K(τ)x(τ) > 0. But this is not possible due to Lemma 8. Therefore, only K0+ = K∗ is possible and the theorem is proved.

Lemma 12 Let (x, K, u, µ) be optimal with adjoint variables z, λ. If x0 > x∗ and K0 < F(x0)/x0, then we must have: λ0 = r, z0 > r′, K0+ > K0.

Proof: Since K0+ = K0 is not allowed (see Lemma 8), we have K0+ > K0 and λ0 = r. Then λ′(0) ≤ 0, and we obtain z0 ≥ r′. If z0 = r′, we would have z′(0) = −ψs(x0) < 0, λ′(0) = 0 and λ′′(0) = −z′(0) > 0. This however contradicts the condition (R).

Let (x, K) be a solution of the system

\[
\begin{align*}
x′ &= −F(x) + Kx, \quad x(0) = x^∗ \\
K′ &= γK, \quad K(0) = K^∗,
\end{align*}
\]

with interval of existence [0, τ). Since K(t) = K∗eγt, x′(0) = 0 and x′′(0) = K∗eγtγx∗ > 0, we have (x(t), K(t)) ∈ (x∗, x) × (K∗, ∞) for t > 0 small. Therefore, it is easy to see that there exists some \(\bar{t}\) ∈ (0, τ) with x(\bar{t}) = \bar{x} and x∗ ≤ x(t) ≤ \bar{x}, t ∈ [0, \bar{t}]. The curve defined by

\[0, \bar{t}] \ni t \mapsto (x(t), K(t)) ∈ [x^*, \bar{x}] × [K^*, ∞)\]

is denoted by Γ1. Note that at t = 0 we have (x′(0), K′(0)) = (0, K∗γ), where K∗γ > 0. In Figure 4 we illustrate the construction of the curve Γ1 for the case of the logistic function.

Lemma 13 There exists a function h1 : [x∗, \bar{x}] → [K∗, ∞) such that

(a) Γ1 = \{(x, h1(x)) | x ∈ [x∗, \bar{x}]\};

(b) h1 is twice continuous differentiable in (x∗, \bar{x}) and monotone increasing.
**Proof:** Note that the system \( \square \) can be transformed into the scalar equation:

\[
\frac{dK}{dx} = \frac{\gamma K}{-F(x) + Kx}, \quad K(x^*) = K^*.
\]

(5)

It becomes clear that \( \Gamma_1 \) has a parameterization \([x^*, \bar{x}] \ni x \mapsto (x, h_1(x)) \in [x^*, \bar{x}] \times [K^*, \infty)\) and the assertions follow.

**Lemma 14** Let \((x, K, u, \mu)\) be optimal with adjoint variables \(z, \lambda\). For \(x_0 > x^*\) and \(K_0 < h_1(x_0)\), the initial conditions have to satisfy \(\lambda_0 = r, \ z_0 > r', \ K_{0,+} \geq h_1(x_0)\).

**Proof:** Assume \(\lambda_0 < r\). We define \(\tau := \sup\{\sigma \geq 0 \mid \lambda(t) < r, \ t \in [0, \sigma]\}\). Due to Corollary \(\square\) \(\tau\) is positive and finite. Then we have \(\lambda(\tau) = r, \ \lambda'(\tau) = 0, \ z(\tau) = r'\). Considering the definition of \(\Gamma_1\), we obtain \(x(t) > x^*, \ t \in (0, \tau)\) due to the values of \(\lambda\). Now, from assumption (V4), the differential equation for \(z\) and \(x(\tau) > x^*\), follow \(z'(\tau) < 0\). Again from the differential equation for \(z\) we obtain \(z(t) > r', \ t \in (0, \tau)\). This implies \(\lambda'(t) < 0, \ t \in (0, \tau)\), which is a contradiction to the definition of \(\tau\). Therefore, \(\lambda_0 = r\) must occur. This implies \(0 \geq \lambda'(0) = r' - z_0\) and \(z_0 \geq r'\) follows.

If \(z_0 = r'\), we would have \(z'(0) = -\psi_*(x_0) < 0, \ \lambda'(0) = 0\) and \(\lambda''(0) = -z'(0) > 0\). This however contradicts the condition (B). Therefore, we must have \(z_0 > r'\).

Assume \(K_{0,+} = K_0\). We know already that \(z_0 > r'\). Then \(\lambda'(0) < 0\) holds and by the same arguments as above (see \(\lambda_0 < r\)) we obtain a contradiction. Therefore, \(K_{0,+} > K_0\) must hold.

If \(K_{0,+} \in (x_0, h_1(x_0))\) we repeat the argumentation above with \(K_0 := K_{0,+} < h_1(x_0)\), obtaining again a contradiction. Thus, we must have \(K_{0,+} \geq h_1(x_0)\).

We denote the curve \([0, K^*] \ni K \mapsto (x^*, K) \in [0, \infty) \times [0, K^*]\) by \(\Sigma^*\). Next we verify that when an optimal trajectory meets the curve \(\Sigma^*\), some properties have to be satisfied.

**Lemma 15** Let \((x, K, u, \mu)\) be optimal with adjoint variables \(z, \lambda\). Let \(x(\sigma) = x^*, \ K(\sigma) \in (0, K^*)\) for some \(\sigma > 0\). Then

\[\lambda(\sigma) = r, \ \lambda'(\sigma) = 0, \ z(\sigma) = r', \ z'(\sigma) = 0.\]

**Proof:** Assume \(\lambda(\sigma) < r\). From the differential equation for \(x\) and \(K\) we obtain \(\tau > \sigma\) with

\[x(\tau) > x^*, \quad F(x(\tau)) - K(\tau)x(\tau) > 0,\]

which is in contradiction to Lemma \(\square\). Thus we must have \(\lambda(\sigma) = r\). Therefore, \(\lambda'(\sigma) = 0, \ z(\sigma) = r'\). Finally, \(z'(\sigma) = 0\) follows from \(\psi_*(x^*) = 0\).

In the neighborhood of \(\Gamma_1\) and \(\Sigma^*\) we have obtained a lot of information concerning the behavior of an extremal trajectory. Lemma \(\square\) ensures that if \(x_0 > x^*\) and \(K_0 < h_1(x_0)\), there must be a jump at \(t = 0\). Furthermore Lemma \(\square\) says that an optimal trajectory \((x(t), K(t))\) does not enter the dashed region in Figure \(\square\).

Our next step is to analyze the behavior of the optimal trajectories that meet the curve \(\Sigma^*\), i.e. \((x(\tau), K(\tau)) \in \Sigma^*\) for some \(\tau > 0\). Since the curve \(\Sigma^*\) is reached by an optimal trajectory
with \( z = r' \), \( \lambda = r \), \( x = x^* \) and \( K \in [0, K^*] \), we use this information to solve the differential equations for \( x, K, z \) and \( \lambda \) backwards in time:

\[
\begin{align*}
x' &= -F(x) + K x, & x(0) &= x^*, \\
K' &= \gamma K, & K(0) &= K_1, \\
z' &= -(z - r')g(x) + \psi_*(x), & z(0) &= r', \\
\lambda' &= -(\lambda - r)\kappa + z - r', & \lambda(0) &= r,
\end{align*}
\]

where \( K_1 \in [0, K^*] \). Such a trajectory eventually comes close to \( (x, K) = (0, 0) \) where we expect an optimal control \( u = 0 \). Therefore, the zeros of the switching variable \( z \) are of interest in this region. Since for \( z(t) < r' \) a value \( \lambda(t) = r \) is not allowed, the behavior of the adjoint variable \( \lambda \) is therefore not so important in this region.

**Lemma 16** For each \( K_1 \in [0, K^*] \), let \((x, z)\) be the solution of

\[
\begin{align*}
x' &= -F(x) + K_1e^{F(x)} x, & x(0) &= x^*, \\
z' &= -(z - r')g(x) + \psi_*(x), & z(0) &= r'.
\end{align*}
\]

Then there exists for each \( K_1 \in (0, K^*) \) \( \tau := \tau_{K_1} = 0 \) with \( x(\tau) = x^* \). Moreover there exists \( \tilde{K}_1 \in (0, K^*) \) such that the following assertions hold:

(a) If \( K_1 \in (0, \tilde{K}_1) \), then \( z \) has a uniquely determined zero \( \sigma \in (0, \tau) \), where \( z'(\sigma) < 0 \) and \( x(\sigma) \in (0, \tilde{x}) \);

(b) If \( K_1 \in (\tilde{K}_1, K^*) \), then \( z(t) > 0 \) for all \( t \in [0, \tau] \);

(c) If \( K_1 = \tilde{K}_1 \), then there is a uniquely determined \( \sigma \) in \((0, \tau)\) with \( z(\sigma) = z'(\sigma) = 0 \); moreover \( x(\sigma) = \tilde{x} \) and \( \tilde{K} := \tilde{K}_1e^{\gamma\sigma} > F(\tilde{x})/\tilde{x} = \tilde{K} \).

**Proof:** Consider the solution \((x, z)\) of (6) with \( K_1 = 0 \). Since \( x_0 = 0 \) is an attracting equilibrium point of \( x' = -F(x) \) (see Remark 3), the solution \( x \) exists for all times \( t \geq 0 \) and \( \lim_{t \to \infty} x(t) = 0 \). Due to this fact \( z \) is also defined for all \( t \geq 0 \). Assume \( z(t) > 0 \) for all \( t > 0 \). As we know, the differential equation may be formulated as \( z' = -zg(x) + \psi(x) \). Since \( \psi \) is negative and continuous in \([0, \tilde{x}]\) (see (V4)), there exists some \( a > 0 \) such that

\[ \psi(\xi) \leq -a, \] for \( \xi \in [0, \tilde{x}] \).

Since \( \lim_{t \to \infty} x(t) = 0 \), there is some \( t_0 > 0 \) with \( x(t) \in [0, \frac{\tilde{x}}{2}], t \geq t_0 \). This implies for \( t \geq t_0 \)

\[ z(t) - z(t_0) = \int_{t_0}^{t} [-z(s)g(x(s)) + \psi(x(s))] ds \leq \int_{t_0}^{t} \psi(x(s)) ds \leq -a(t - t_0). \]

But this contradicts the hypothesis on \( z \). Thus, there must be a \( \sigma > 0 \) with \( z(\sigma) = 0 \) and \( z(t) > 0, t \in (0, \sigma) \). Then \( z'(\sigma) \leq 0 \), \( \psi(x(\sigma)) \leq 0 \), and therefore \( x(\sigma) \leq \tilde{x} \). Due to

\[ 0 \leq z''(\sigma) = -z'(\sigma)g(x(\sigma)) + \psi'(x(\sigma))x'(\sigma) = -z'(\sigma)g(x(\sigma)) - \psi'(x(\sigma))F(x(\sigma)) \]

and assumption (V5), \( z'(\sigma) = 0 \) cannot occur. Therefore, \( z'(\sigma) < 0 \), \( x(\sigma) < \tilde{x} \) and \( z(t) < 0 \) for \( t > \sigma \) due to the differential equation for \( z \). By continuity arguments, we may choose a maximal \( \tilde{K}_1 > 0 \) such that for the solution \((x, z)\) of (6) with \( K_1 \in [0, \tilde{K}_1] \) there exists \( \tau > 0 \) and \( \sigma \in (0, \tau) \) with \( x(\tau) = x^* \),

\[ z(t > 0), \ t \in [0, \sigma], \ z(\sigma) = 0, \ z(t < 0), \ t \in (\sigma, \tau); \]
proving (a) and (b).

Now we prove (c). From the construction of \( \tilde{K}_1 \) and due to the differential equation for \( x \) we obtain \( z(\sigma) = 0 \) and \( x(\sigma) > 0 \). Since \( \tilde{K}_1 \) is maximal, we have \( z(\sigma) = z'(\sigma) = 0 \). We cannot have \( x(\sigma) > \bar{x} \), since \( z'(\sigma) = -\psi(x(\sigma)) < 0 \). The case \( x(\sigma) < \bar{x} \) cannot be occur, since \( z'(\sigma) = -\psi(x(\sigma)) > 0 \). Therefore, we must have \( x(\sigma) = \bar{x} \).

We cannot have \( K(\sigma)x(\sigma) < F(x(\sigma)) \) since, due to \( z''(\sigma) = \psi'(x(\sigma))x'(\sigma) < 0 \), \( z \) would be negative in a neighborhood of \( \sigma \). Otherwise, if we had \( K(\sigma)x(\sigma) = F(x(\sigma)) \), i.e. \( K(\sigma)\bar{x} = F(\bar{x}) \), then \( z \) would be positive in a neighborhood of \( \sigma \), due to \( z''(\sigma) = 0 \) and \( z''(\sigma) = \psi'(x(\sigma))x''(\sigma) = \psi'(x(\sigma))\gamma F(\bar{x}) > 0 \). Thus, we must have \( K(\sigma) > F(\bar{x})/\bar{x} \) and (c) is proved.

**Corollary 17** Let \( \tilde{K}_1 \in (0, K^*) \) be chosen as in Lemma 16. Let \( K_1 \in [0, \tilde{K}_1] \) and \( (x, z) \) the corresponding solution of (6). Then there exists a continuous mapping \( l : [0, K_1] \to (0, \infty) \) and \( \tilde{x} \in (0, \bar{x}) \), such that

(a) \( x(l(0)) = \bar{x}, x(l(\tilde{K}_1)) = \tilde{x} \);

(b) \( z(l(K_1)) = 0, K_1 \in [0, \tilde{K}_1], z'(l(K_1)) < 0, K_1 \in [0, \tilde{K}_1], z'(l(\tilde{K}_1)) = 0 \);

(c) \( l \) is continuous differentiable in \( (0, \tilde{K}_1) \) and \( l'(K_1) > 0, K_1 \in (0, \tilde{K}_1) \).

**Proof:** Let \( K_1 = 0 \) and let \( \sigma > 0 \) with \( z(\sigma) = 0 \) (see proof of Lemma 16). Now define \( \tilde{x} := x(\sigma) \). Given \( K_1 \in (0, \tilde{K}_1) \), we denote by \( x := x(\cdot; K_1), z := z(\cdot; K_1) \) the corresponding solution of (6) and define \( l(K_1) := \sigma \), where \( \sigma > 0 \) is the uniquely determined zero of \( z(\cdot; K_1) \) (see Lemma 16). Then (b) holds. The mapping \( K_1 \to l(K_1) \) is continuous since \( z \) depends continuously on \( K_1 \) (notice that \( z'(\sigma) < 0 \)). Now we may extend \( l : (0, \tilde{K}_1) \to (0, \infty) \) to a continuous map on \( [0, \tilde{K}_1] \), proving (a). Notice that the mapping \( \Psi : [0, \tau] \times [0, \tilde{K}_1] \to \mathbb{R} \) defined by \( \Psi(s, K_1) := z(s; K_1) \) is differentiable and

\[ \frac{\partial \Psi}{\partial s}(s, K_1) = z'(s; K_1), \quad \frac{\partial \Psi}{\partial K_1}(s, K_1) = v(s; K_1), \]

where \( v := v(\cdot; K_1) := \frac{\partial z}{\partial K_1} (\cdot; K_1) \) is the solution of the initial value problem

\[ v' = -vg(x(t; K_1)) + \left[ -\left( z(t; K_1) - r' \right)g'(x(t; K_1)) + \psi'(x(t; K_1)) \right] w, \quad v(0) = 0, \]

and \( w := \frac{\partial x}{\partial K_1} \) solves

\[ w' = \left[ -F'(x(t; K_1)) + K_1 e^{x(t; K_1)} \right] w + e^{x(t; K_1)}, \quad w(0) = 0. \]

By the implicit function theorem applied on \( \Psi(l(K_1), K_1) = 0 \) for \( K_1 \in (0, \tilde{K}_1) \) we have

\[ z'(l(K_1); K_1) l'(K_1) = -v(l(K_1); K_1), \quad z'(l(K_1); K_1) < 0, \quad K_1 \in (0, \tilde{K}_1), \]

(7)

It is obvious that \( v(t) > 0 \) for all \( t > 0 \), since (s) as well as \( w(t) \) are positive for \( t \in (0, l(K_1)) \). From (7) we obtain \( l'(K_1) > 0, K_1 \in (0, \tilde{K}_1) \), and (c) is proved.

Corollary 17 allows us to define a curve \( \Sigma_0 \), parameterized by

\[ \xi : [0, \tilde{K}_1] \to [0, \bar{x}] \times [0, \tilde{K}] \]

\[ K_1 \mapsto (x(l(K_1); K_1), K_1 e^{y(l(K_1))}) \]
(see the proof of Corollary 17 for the notation). From Lemma 16 and Corollary 17 we conclude that for the solutions \((x, K, z)\) of
\[
\begin{align*}
x' &= -F(x) + Kx, \quad x(0) = x^*, \\
z' &= -(z - r')g(x) + \psi_+(x), \quad z(0) = r', \\
K' &= \gamma K, \quad K(0) = K_1 \in [0, K^*]
\end{align*}
\]
one of the following alternatives holds:
(i) if \(K_1 \in (\tilde{K}_1, K^*]\), then \(z(t) > 0\), for all \(t \geq 0\) (see curve \(\gamma_1\) in Figure 2);
(ii) if \(K_1 = \tilde{K}_1\), then \(z(t) > 0\) except at a single time point, where \((x, K) = (\tilde{x}, \tilde{K})\) holds; (see curve \(\gamma_2\) in Figure 2);
(iii) if \(K_1 \in [0, \tilde{K}_1)\), then \(z(t) > 0\), before the trajectory intercept \(\Sigma_0\) and \(z(t) < 0\) after that (see curve \(\gamma_3\) in Figure 2).

**Corollary 18** Let \(\tilde{K}_1, \tilde{x}, \tilde{\tilde{x}}\) and \(l\) be defined as in Lemma 16 and in the proof of Corollary 17. Then there exists \(\tilde{x} \in (\tilde{x}, \tilde{\tilde{x}})\), \(\tilde{K} > 0\) and a continuous mapping \(h_0 : [\tilde{x}, \tilde{\tilde{x}}] \to [\tilde{K}, \tilde{\tilde{K}}]\) with
\[
\Sigma_0 \cap \{(x_0, K_0) | F(x_0) \leq K_0x_0\} = \{(x_0, h_0(x_0)) | x_0 \in [\tilde{x}, \tilde{\tilde{x}}]\}.
\]
Moreover:
(a) \(h_0(\tilde{x}) = \tilde{K}\), \(h_0(\tilde{\tilde{x}}) = \tilde{\tilde{K}}\), \(F(\tilde{x}) = \tilde{\tilde{K}}\tilde{x}\);
(b) \(h_0\) is continuous differentiable in \((\tilde{x}, \tilde{\tilde{x}})\) and \(h_0'(x) > 0\), \(x \in [\tilde{x}, \tilde{\tilde{x}}]\).

**Proof:** Consider the mapping
\[
\xi : [0, \tilde{K}_1] \ni K_1 \mapsto (x(l(K_1); K_1), z(l(K_1); K_1)) \in [0, \tilde{x}] \times \mathbb{R},
\]
where \(x(\cdot; \cdot)\) and \(z(\cdot; \cdot)\) are defined as in the proof of Corollary 17. Then
\[
\xi'(K_1) = \left(x'(l(K_1); K_1)l'(K_1) + \frac{\partial x(\cdot; \cdot)}{\partial K_1}(l(K_1); K_1), z'(l(K_1); K_1)l'(K_1) + \frac{\partial z(\cdot; \cdot)}{\partial K_1}(l(K_1), K_1)\right)
\]
and we see by the implicit function theorem that the region \(\Sigma_0 \cap \{(x_0, K_0) | F(x_0) \leq K_0x_0\}\) may be reparameterized by a function \(h_0\). Notice that the implicit function theorem may be used due to Corollary 17. The condition \(h_0'(x) > 0\) follows from the same corollary.

Let \((x, K)\) be the solution of the initial value problem
\[
\begin{align*}
x' &= -F(x) + Kx, \quad x(0) = \tilde{x}, \\
K' &= \gamma K, \quad K(0) = \tilde{\tilde{K}}
\end{align*}
\]
in the interval \([0, \tau]\). Similar to the definition of \(\Gamma_1\) we obtain \(\tilde{t} \in (0, \tau)\) with \(x(\tilde{t}) = \tilde{x}\). We denote the curve
\[
[0, \tilde{t}] \ni t \mapsto (x(t), K(t)) \in [\tilde{x}, \tilde{\tilde{x}}] \times [\tilde{\tilde{K}}, \infty)
\]
by \(\Gamma_3\). (In Figure 2 one can recognize \(\Gamma_3\) as the part of the curve \(\gamma_2\) with \(x > \tilde{x}\) and \(K > \tilde{\tilde{K}}\).)

Now let \((x, K)\) be the solution of the initial value problem
\[
\begin{align*}
x' &= F(x) - Kx, \quad x(0) = \tilde{x}, \\
K' &= -\gamma K, \quad K(0) = \tilde{\tilde{K}}
\end{align*}
\]
This solution meets the curve $\Sigma^*$ in $(x^*, \bar{K}_1)$ for some $\tau > 0$ (see Lemma 16). The curve defined by this trajectory is called $\Gamma_2$. (In Figure 2, the curve $\Gamma_2$ corresponds to the part of $\gamma_2$ with $K < \bar{K}$.) The last curve we define is $\Gamma_4$, which is parameterized by the solution $(x, K)$ of

$$
\begin{aligned}
  x' &= -F(x) - Kx, \quad x(0) = x_0, \\
  K' &= -\gamma K, \quad K(0) = K_0+,
\end{aligned}
$$

Note that the solution exists in $[0, \infty)$ and $x'(0) < 0$, $K'(0) > 0$ (see Figure 3).

Now we come back to the region $x > x^*$, more specifically, above the curve $\Gamma_1$. We already know that if the initial condition $(x_0, K_0)$ lays below $\Gamma_1$, then $K_{0,+} > h_1(x_0)$ must hold. We want to determine a curve $\Sigma_s$, above $\Gamma_1$, upon which the trajectories must jump for this initial conditions, i.e. $(x_0, K_0) \in \Sigma_s$. In order to be able to construct such a curve $\Sigma_s$, we need the fact that there exists $(x_0, K_0) \in (x^*, \bar{x}) \times (K^*, \infty)$ such that the solution $(x, K, z, \lambda)$ of

$$
\begin{aligned}
  x' &= F(x) - Kx, \quad x(0) = x_0, \\
  K' &= -\gamma K, \quad K(0) = K_0+, \\
  z' &= (z - r')g(x) - \psi_s(x), \quad z(0) = z_0, \\
  \lambda' &= (\lambda - r)\kappa - z + r', \quad \lambda(0) = r,
\end{aligned}
$$

meets the curve $\Sigma^*$.

**Lemma 19** There exists $\tilde{K}_2 \in (0, \bar{K}_1)$, $\tilde{K}_3 \in (\tilde{K}_1, K^*)$ and $a > 0$ such that the solution $(x(\cdot; K_1), z(\cdot; K_1), \lambda(\cdot; K_1))$ of the system

$$
\begin{aligned}
  x' &= F(x) + K_1 e^{\gamma t} x, \quad x(0) = x^*, \\
  z' &= -(z - r')g(x) + \psi_s(x), \quad z(0) = r', \\
  \lambda' &= -(\lambda - r)\kappa + z - r', \quad \lambda(0) = r,
\end{aligned}
$$

exists in $[0, a]$ for each $K_1 \in (\tilde{K}_2, K^*)$. Moreover, for each $K_1 \in (\tilde{K}_3, K^*)$ there exist numbers $\rho(K_1), \sigma(K_1), \tau(K_1)$ with

(a) $0 < \rho(K_1) < \sigma(K_1) < \tau(K_1) < a$;
(b) $x(t; K_1) \leq x^*, \ t \in (0, \rho(K_1))$, $x(\rho(K_1); K_1) = x^*$, $x(t; K_1) > x^*, \ t \in (\rho(K_1), a]$, and $x(a; K_1) \geq \bar{x}$;
(c) $0 < z(t; K_1) < r', \ t \in (0, \sigma(K_1))$, $z(\sigma(K_1); K_1) = r'$, $z(t; K_1) > r', \ t \in (\sigma(K_1), a]$;
(d) $\lambda(t; K_1) < r, \ t \in (0, \tau(K_1))$, $\lambda(\tau(K_1); K_1) = r$, $\lambda'(\tau(K_1); K_1) > 0$;
(e) $\lim_{K_1 \rightarrow K^*} \tau(K_1) = 0$.

**Proof:** Since the trajectory for $K_1 := K^*$ corresponds to $\Gamma_1$ we can choose $a > 0$ and $\tilde{K}_2 \in (0, \bar{K}_1)$ with $x(a; K_1) \geq \bar{x}$, $K_1 \in (\tilde{K}_2, K^*)$. It follows from the differential equations for $z$ and $\lambda$ that $z(t; K^*) > r'$, $\lambda(t; K^*) > r$, $t \in (0, a]$. Let $\varepsilon \in (0, a)$ be given. Choose $\beta > 0$ and $\tilde{K}_3 \in (\tilde{K}_1, K^*)$ such that for each $K_1 \in (\tilde{K}_3, K^*)$

$$
  z(t; K_1) \geq r' + \beta, \quad \lambda(t; K_1) \geq r + \beta, \quad t \in [\varepsilon, a].
$$

This can be done due to the fact that the solution of (11) depends continuously on the parameter $K_1$.  

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Let $K_1 \in (\tilde{K}_3, K^*)$ and set $(x, z, \lambda) := (x(\cdot; K_1), z(\cdot; K_1), \lambda(\cdot; K_1))$. Then we see that there exists $\rho(K_1) > 0$ with the property in (b).

Since $z''(0) = \psi''(x^*) x'(0) < 0$ and since $z(a) \geq r'$, we obtain $\sigma(K_1) > 0$ with $z(\sigma(K_1)) = \tau'$ and $0 < z(t) < \tau'$, $t \in (0, \sigma(K_1))$. $\sigma(K_1) < \rho(K_1)$ cannot hold since $z''(\sigma(K_1)) = \psi''(x(\sigma(K_1))) < 0$. $\sigma(K_1) = \rho(K_1)$ cannot hold since $z''(\sigma(K_1)) = z''(\rho(K_1)) = \psi''(x(\rho(K_1))) > 0$. From the differential equation for $\xi$ and the fact that $\rho(K_1) < \sigma(K_1)$ we conclude $z(t) > \tau'$, $t > \sigma(K_1)$. Repeating the argumentation above we obtain $\tau(K_1)$ with $\lambda(\tau(K_1)) = r$, $\lambda(t) < r$, $0 < t < \tau(K_1)$).

The value $\tau(K_1)$ according to Lemma 19 is locally uniquely determined and the same is true for $K(\tau(K_1))$. We want to identify $K(\tau(K_1))$ as a value $K_{0,+}$, when an extremal trajectory starts in the initial value $(x_0, K_0) \in (x^*, \tilde{x}) \times [0, \infty)$, with $K_0 < h_1(K_0)$. To do this we need more information concerning the mapping $K_1 \mapsto \tau(K_1)$.

Consider the system (11) for $K_1 \in (\tilde{K}_3, K^*)$ and let $(x, \lambda, z)$ be the corresponding solution. To make clear the dependence of $\lambda$ on $K_1$, we denote it by $G(\cdot; K_1)$. The equation

$$G(\tau; K_1) = r$$

(12)

describes the fact that the solution $G(\cdot; K_1)$ has the value $r$ at time $\tau$. In order to find the jump curve $\Sigma$, we try to resolve (12) with respect to $\tau$. Note that from Lemma 19 we know that there are solutions of (12).

Lemma 20 Using the notations of Lemma 19 the following assertions hold:

(a) There exists $\tilde{K}_1 \in [\tilde{K}_1, K^*)$ and a continuous differentiable mapping $g_r : (\tilde{K}_1, K^*) \to (0, \infty)$ with

$$G(g_r(K_1); K_1) = r, \ K_1 \in (\tilde{K}_1, K^*)$$

(13)

(b) $g'_r(K_1) < 0$ for all $K_1 \in (\tilde{K}_1, K^*)$;

(c) $x(g_r(\tilde{K}_1); \tilde{K}_1) \in \Gamma_3$ or $\tilde{K}_1 = \tilde{K}_1$ and $x(g_r(\tilde{K}_1); \tilde{K}_1) = \tilde{x}$.

Proof: Let $K_1 \in (\tilde{K}_3, K^*)$. Since $\lambda = G(\cdot; K_1)$, the function $G$ is obviously differentiable and we have

$$\frac{\partial G}{\partial \tau}(\tau(K_1); K_1) = \lambda'(\tau(K_1)) > 0$$

(see Lemma 19). With the implicit function theorem we obtain a neighborhood $U$ of $K_1$ and a function $g_r : U \to (0, \infty)$ such that $G(g_r(K_1); K_1) = r, K_1 \in U$ holds. The implicit function theorem implies more: $g_r$ can be extended in a maximal way to $(\tilde{K}_1, K^*)$ with $\tilde{K}_1 \in [\tilde{K}_1, K^*)$ and (13) holds. The properties in c) are a consequence of the maximality of the extension. Moreover:

$$\lambda'(g_r(K_1))g'_r(K_1) = -v(g_r(K_1)),$$

where $v := \frac{\partial \lambda}{\partial K_1}(\cdot)$ solves

$$v' = -\kappa v + w, \ v(0) = 0.$$
It follows obviously that the continuation ends at the "boundary"
starting in \((\tilde{x}, \lambda)\). As we will see in Theorem 29 an optimal trajectory
\((\Sigma)\) with the values
\[w := \frac{\partial y}{\partial K_1}(\cdot)\] solves
\[w' = -wg(x(t)) + \left[ - (z(t) - r')g'(x(t)) + v'_z(x(t)) \right] y, \ w(0) = 0,\]
and
\[y := \frac{\partial x}{\partial K_1}(\cdot)\] solves
\[y' = \left[ - F'(x(t)) + K_1 e^{\gamma t} \right] y + e^{\gamma t} x(t), \ y(0) = 0.\]
Obviously \(y(t) > 0, \ t \in (0, g_r(K_1)). \) Since \(- (z(t) - r')g'(x(t)) + v'_z(x(t)) > 0\) for each \(t \in (0, g_r(K_1)), \) we have \(w(t) > 0, \ t \in (0, g_r(K_1)), \) and therefore \(v(t) = \frac{\partial \lambda}{\partial K_1}(t) > 0, \ t \in (0, g_r(K_1)). \) It follows \(g'_r(K_1) < 0. \)

Now, we have to distinguish two cases:

**Case I** \(x(g_r(\hat{K}_1), \hat{K}_1) \in \Gamma_3 \) and \(x(g_r(\tilde{K}_1), \tilde{K}_1) < \tilde{x}; \)

**Case II** \(x(g_r(\tilde{K}_1), \tilde{K}_1) = \tilde{x}. \)

In each case we have a curve \(\Sigma_s\) defined by
\[\left[\tilde{K}_1, K^* \right] \ni \tilde{K}_1 \mapsto (x(g_r(K_1), K_1), K_1 e^{\gamma g_r(K_1)}) \in [x^*, \tilde{x}] \times [K^*, \infty). \]

In case II this curve ends at the "boundary" \(\tilde{x}. \) In case I we want to continue this curve such that the continuation ends at the "boundary" \(\tilde{x}. \) For this continuation the trajectories starting in \((\tilde{x}, K), \ K \geq \tilde{K}, \) come into consideration. To analyze the situation we need the curve \(\tilde{\Sigma}\) which is defined by
\[\tilde{\Sigma} : [0, \infty) \ni K \mapsto (\tilde{x}, K) \in [0, \tilde{x}] \times [0, \infty). \]

(See Figure 3. As we will see in Theorem 29 an optimal trajectory \((x, K)\) with adjoint variables \((z, \lambda)\) meets the curve \(\tilde{\Sigma}\) with the values
\[z(\sigma) = 0, \ z'(\sigma) = 0, \ \lambda(\sigma) < r. \]

This motivates the construction of the continuation of \(\Sigma_s\) in the following way: Compute trajectories \((x, K, z)\) backwards in time starting with initial values
\[x(0) = \tilde{x}, \ K(0) = K_0 > \tilde{K}, \ z(0) = 0. \]

**Lemma 21** There exists \(\tilde{K}_1 > \tilde{K}\) and \(a > 0\) such that for each \(K_1 \geq \tilde{K}_1\)
\[x(a; K_1) = \tilde{x}, \ z(t; K_1) < r', \ t \in [0, a], \]
where \((x(\cdot; K_1), z(\cdot; K_1))\) is the solution of
\[
\begin{cases}
x' = -F(x) + K_1 e^{\gamma t} x, \ x(0) = \tilde{x}, \\
z' = -(z - r')g(x) + v_z(x), \ z(0) = 0.
\end{cases}
\]

**Proof:** Let \(\varepsilon > 0. \) It follows from the differential equation for \(x\) that the solution \(x(\cdot; K_1)\) reaches \(x = \tilde{x}\) for a time \(t_1 < \varepsilon\) if \(K_1\) is sufficiently large. Since the differential equation for \(z\) may be considered as a linear equation (if we plug in \(x(\cdot; K_1)\)) the value \(z = r'\) cannot be reached in the time interval \([0, \varepsilon]\) if \(K_1\) is sufficiently large. \(\blacksquare\)
As we know from the results above an optimal trajectory \((x, K)\) with adjoint variables \((z, \lambda)\) starts in \((\tilde{x}, \tilde{K})\) in the following way:

\[
x(0) = \tilde{x}, \quad K(0) = \tilde{K}, \quad z(0) = 0, \quad \tilde{\lambda} := \lambda(0) < r.
\]

For each \(K_1 > \tilde{K}\) there exists a time \(\xi = \xi(K_1)\) with \(K_1 e^{-\gamma \xi} = \tilde{K}\). Set \(\Lambda(K_1) := \lambda(\xi; K_1)\) where \(\lambda(\cdot; K_1)\) is the solution of

\[
\lambda' = - (\lambda - r) \kappa - r', \quad \lambda(0) = \tilde{\lambda}.
\]

Now consider for each \(K_1 > \tilde{K}\) the solution of

\[
\begin{align*}
x' &= -F(x) + K_1 e^{\gamma t} x, \quad x(0) = \tilde{x}, \\
z' &= -(z - r') g(x) + \psi_*(x), \quad z(0) = 0, \\
\lambda' &= - (\lambda - r) \kappa + z - r', \quad \lambda(0) = \Lambda(K_1).
\end{align*}
\]

We want to find for \(K_1 > \tilde{K}\) some time \(\tau(K_1)\) such that \(\lambda(\tau(K_1); K_1) = r\) holds. Again we use the notation \(G(\cdot; K_1) := \lambda(\cdot; K_1)\).

Lemma 22 In case I the following assertions hold:

(a) There exists \(\tilde{K}_1 \in (\tilde{K}, \infty)\) and a continuous differentiable mapping \(g_r : (\tilde{K}, \tilde{K}_1) \to (0, \infty)\) with

\[
G(g_r(K_1); K_1) = r, \quad K_1 \in (\tilde{K}, \tilde{K}_1).
\]

(b) \(g_r'(K_1) < 0\) for all \(K_1 \in (\tilde{K}, \tilde{K}_1)\).

(c) \(x(g_r(\tilde{K}_1); \tilde{K}_1) = \tilde{x}\).

Proof: This can be proved similar to Lemma 20. The main observation is that we have \(z(\tau; K_1) > r'\) if \(\lambda(\tau; K_1) = r\). The result of (c) is a consequence of Lemma 21.

Now we have constructed a curve \(\Sigma_s\) connecting \((x^*, K^*)\) with \((\tilde{x}, \tilde{K})\), where \(\tilde{K} := \tilde{K}_1 e^{\gamma g_r(\tilde{K}_1)}\).

Since this curve should be used as a jump curve in the region \([x^*, \tilde{x}] \times [0, \infty)\), we want to reparameterize this curve in such a way that \([x^*, \tilde{x}]\) is the parameter interval. But to do this we need the fact that the following function

\[
[\tilde{K}_1, K^*] \cup [\tilde{K}, \tilde{K}_1] \ni K_1 \mapsto x(g_r(K_1); K_1) \in [x^*, \tilde{x}]
\]

is monotone increasing. Unfortunately, we are not able to prove this. The fact we can prove is that the mapping

\[
H : [\tilde{K}_1, K^*] \ni K_1 \mapsto x(g_r(K_1); K_1) \in [x^*, \tilde{x}]
\]

is monotone increasing in a neighborhood of \(K^*\).

Lemma 23 There exists \(K_+ \in [\tilde{K}_1, K^*]\) and \(m_0, m_1 > 0\) such that

a) \(\tau(K^*) = 0\);

b) \(\tau'(K^*) = - \frac{4}{\gamma K^*}\), \(\tau\) is differentiable in \([K_+, K^*]\);

c) \(-m_1(K^* - K) \leq \tau(K) \leq -m_0(K^* - K)\) for all \(K \in [K_+, K^*]\).
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Proof: Item a) is obvious. Clearly, $\tau$ is differentiable in $[K_+, K^*)$. From the identity

$$\lambda(\tau(K); K) = 0, K \in [\hat{K}_1, K^*),$$

we obtain

$$\lambda'(\tau(K); K)\tau'(K) + \nu(\tau(K); K) = 0, K \in [\hat{K}_1, K^*).$$

Here we have used the notation of Lemma 19. Due to the fact that $\lambda'(\tau(K); K) > 0$ for each $K \in [\hat{K}_1, K^*)$ we have

$$\tau'(K) = -\frac{\nu(\tau(K); K)}{\lambda'(\tau(K); K)}, K \in [\hat{K}_1, K^*).$$

Using Taylor’s expansion for $\nu$ and $\lambda$ we obtain

$$\tau'(K) = \frac{1}{6}v''''(\xi; K)\frac{1}{24}\lambda^{(iv)}(\eta; K), K \in [\hat{K}_1, K^*),$$

where $\xi, \eta, \in (0, \tau(K))$. From this we can conclude

$$\tau'(K^*) = -\frac{1}{6}v''''(0; K^*)\frac{1}{24}\lambda^{(iv)}(0; K^*) = -\frac{4}{\gamma K^*}.$$  

The result in c) is a consequence of the estimate in b) by using continuity arguments. ■

Lemma 24 There exists $K_+ \in [\hat{K}_1, K^*)$ such that

$$H(K^*) = x^*, H'(K^*) = 0; H'(K) > 0, K \in (K_+, K^*).$$

Proof: Let $K_+$ be chosen as in Lemma 23. We have

$$H'(K) = x'(\tau(K); K)\tau'(K) + y(\tau(K); K), K \in [K_+, K^*],$$

and by Lemma 23 we have $H'(K^*) = 0$. From the differential equation for $y$ we obtain that there exists $M > 0$ such that

$$y(\tau(K); K) \geq M\tau(K), K \in [K_+, K^*].$$

Since $\tau'$ is bounded in $[K_+, K^*]$ and since $x'(\tau(K); K) = 0$ we obtain the assertion, eventually by making $K_+$ larger. ■

Corollary 25 There exists $x_s \in (x^*, \bar{x}]$ and a continuously differentiable mapping $h_s : [x^*, x_s]$ such that

$$(x, h_s(x)) \in \Sigma_s, x \in [x^*, x_s].$$

Proof: The mapping $h_s$ can be found by reparameterizing the curve

$$K_1 \mapsto (x(g_r(K); K), K(g_r(K); K))$$

using the results of Lemma 24. ■

Now the jump curve $\Sigma_s$ allow us to find, given $(x_0, K_0)$ with $x_0 \in (x^*, x_s)$ and $K_0 < h_s(x_0)$, the optimal initial value $K_{0,+} := h_s(K_0)$. Notice that in the region around $\Gamma_1$, $\Sigma^*$, and $\Sigma_s$, the behavior of the extremals is rather clear. Notice also that $h_s(x) > h_1(x)$, for $x \in (x^*, \bar{x})$, since $\Sigma_s$ is above $\Gamma_1$. From the construction of $\Sigma_s$ and $\Gamma_3$, we may have two cases: $\Sigma_s$ and $\Gamma_3$ have a point in common; $\Sigma_s$ and $\Gamma_3$ do not intersect. In the next section we are able to find for each initial condition $(x_0, K_0) \in (0, \bar{x}) \times (0, \infty)$ the corresponding optimal trajectory for the case where $\Sigma_s$ and $\Gamma_3$ do not intersect; the other case can be handled in an analogous way.
4 Optimal trajectories

In this section we summarize the previous results, in order to design a complete picture of the optimal trajectories. We are also able to determine the correspondent optimal controls, based on the information we obtain from the previous analysis. Let us consider the regions defined by

$$\Sigma^*, \tilde{\Sigma}, \Sigma_s, \Sigma_0, \Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4$$

in \([0, \bar{x}] \times [0, \infty)\). In Figure 4 we present a sketch of the five main regions for the case of the logistic function. Figure 4 shows the case that \(x_s \geq \bar{x}\) holds. The analysis in the following is done under the following assumption:

$$x_s = \bar{x}.$$  

Unfortunately, we are not able to present reasonable conditions which imply this assumption.

**Domain (R1):** boundaries \(\Sigma^*, \Sigma_s, \{ (x, K) \in [0, \bar{x}] \times [0, \infty) \mid x = \bar{x} \}; \)

**Domain (R2):** boundaries \(\Sigma_0, \Sigma^*, \Sigma_s, \Gamma_3\) and eventually \(\{ (x, K) \in [0, \bar{x}] \times [0, \infty) \mid x = \bar{x} \}; \)

**Domain (R3):** boundaries \(\{ (x, K) \in [0, \bar{x}] \times [0, \infty) \mid x = 0 \}; \Sigma_0, \Gamma_4; \)

**Domain (R4):** boundaries \(\{ (x, K) \in [0, \bar{x}] \times [0, \infty) \mid x = 0 \}; \Gamma_4, \tilde{\Sigma}; \)

**Domain (R5):** boundaries \(\tilde{\Sigma}, \Gamma_3, \{ (x, K) \in [0, \bar{x}] \times [0, \infty) \mid x = \bar{x} \}. \)

**Remark 26** In the following we may assume, without loss of generality, that \(K_0 = K_{0,+}\) holds since in the case of \(K_0 < K_{0,+}\) we may leave the region where we started or not. In the first case we have to apply the discussion in another region, in the second case we have to repeat the analysis in the same region with \(K_0 := K_{0,+}.\) \square

**Theorem 27** Let \((x, K, u, \mu)\) be optimal with adjoint variables \(z, \lambda). The following assertions hold:

(a) Let \((x_0, K_0)\) be in (R1). Then \(z_0 > r', \lambda_0 = r, (x_0, K_{0,+}) \in \Sigma_s\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \Sigma^*\) and \(u \equiv 1, \mu \equiv 0\) in \((0, \tau)\);

(b) Let \((x_0, K_0)\) be in (R2). Then \(z_0 > 0, \lambda_0 < r\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \Sigma^*\) and \(u \equiv 1, \mu \equiv 0\) in \((0, \tau)\);

(c) Let \((x_0, K_0)\) be in (R3). Then \(z_0 < 0, \lambda_0 < r\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \Sigma_0\) and \(u \equiv 0, \mu \equiv 0\) in \((0, \tau)\);

(d) Let \((x_0, K_0)\) be in (R4). Then \(z_0 < 0, \lambda_0 < r\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \tilde{\Sigma}\) and \(u \equiv 0, \mu \equiv 0\) in \((0, \tau)\);

(e) Let \((x_0, K_0)\) be in (R5). Then \(z_0 < 0, \lambda_0 < r\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \tilde{\Sigma}\) and \(u \equiv 1, \mu \equiv 0\) in \((0, \tau)\).

**Proof:** Ad (a): We actually prove only that if \((x_0, K_0)\) is in (R1), then \(K_{0,+} \geq h_s(x_0)\), i.e. we must jump either to (R2) or to (R5). Later on, in the proof of items (b) and (e), we will see that the initial condition \(\lambda_0 = r\) is not allowed in these regions. The last possible case: \((x_0, K_{0,+}) \in \Gamma_3\) is excluded in Theorem 28.

From Lemma 14 it is enough to consider initial conditions \((x_0, K_0)\) with \(K_0 \geq h_1(x_0)\). Assume
λ_0 < r. Then there exists a τ > 0 with λ(τ) = r and λ(t) < r, t ∈ [0, τ). Consequently λ'(τ) = 0, z(τ) = r', z'(τ) = −ψ_s(x(τ)).

We consider three cases: i) z'(τ) < 0: then λ''(τ) > 0, contradicting (R). ii) z'(τ) > 0: then x(τ) < x^* and (x(τ), K(τ)) ∈ \( \bigcup_{i=2}^6 R_i \) ∪ Σ ∪ Σ_0 ∪ Γ_2 ∪ Γ_3 ∪ Γ_4. As we will see, the initial condition λ_0 = r is not allowed in these regions (curves), and again we have a contradiction.

iii) z'(τ) = 0: then x(τ) = x^*. From Lemma 9 K(τ) > K^* cannot occur and we must have (x(τ), K(τ)) ∈ Σ^*. From the differential equation for \( (x,K) \), follows the existence of \( σ ∈ (0, τ) \) such that \( (x(σ), K(σ)) \) ∈ Σ_s. However, \( λ(σ) < r \), contradicting the construction of Σ_s, since the optimal trajectory \( (x,K) \) hits the curve Σ^*.

Therefore, we must have \( λ_0 = r \), what implies \( z_0 ≥ r' \). Note that \( z_0 = r' \) is not possible, since we would have \( λ'(0) = 0 \) and \( λ''(0) = −z'(0) = ψ_s(x_0) > 0 \), contradicting (R). Finally, we exclude the case \( K_{0,s} < h_s(x_0) \). If this where not the case, we would obtain a contradiction arguing as in the case \( λ_0 < r \) above.

Ad (b): Assume \( λ(0) = r \). Then \( λ'(0) < 0 \) and \( z_0 ≥ r' \).

If \( z_0 = r' \), then \( λ'(0) = 0 \) and we have three possible cases: i) \( x_0 > x^* \): we have \( λ''(0) = ψ_s(x_0) > 0 \), contradicting (R); ii) \( x_0 = x^* \): cannot occur, due to Lemma 9 \( x_0 < x^* \): then \( z'(0) > 0 \) and \( λ''(0) = −z'(0) < 0 \). Since \( λ(τ) < r \) for all \( t > 0 \) is not possible, there exists \( τ > 0 \) with \( λ(τ) = r \), \( λ(t) < r, t ∈ (0, τ) \). Then \( λ'(τ) = 0, z(τ) = r' \) and there exists \( σ ∈ (0, τ) \) with \( z'(σ) = 0, z(σ) > r' \). From the differential equation for \( z \) we conclude with (V4) that \( x(τ) ≥ x(σ) > x^* \).

This is a contradiction to Lemma 8, since it is easy to see that \( x(τ) K(τ) < F(x(τ)) \).

For \( z_0 > r' \) we have again three possible cases: i) \( x_0 > x^* \); ii) \( x_0 = x^* \); iii) \( x_0 < x^* \). Cases ii) and iii) are excluded analogous as above. In case i), since \( λ'(0) < 0 \), there exists \( τ > 0 \) such that \( λ(τ) = r \), \( λ'(τ) = 0, z(τ) = r' \), \( z'(τ) = −λ''(τ) ≥ 0 \). Therefore, we have \( x(τ) ≤ x^* \). If \( x(τ) < x^* \), follows from \( (x_0, K_0) ∈ (R_2) \) and the fact that there are no jumps in interval \( (0, τ) \) that \( (x(τ), K(τ)) \) ∈ (R_2) must hold. In this case a contradiction can be obtained arguing as in the case \( λ(0) = r \) & \( z(0) = r' \) above. If \( x(τ) = x^* \), follows from Lemma 9 that \( K(τ) > K^* \) cannot occur. Thus, we must have \( x(τ), K(τ) \) ∈ Σ^*. However, from the construction of Σ_s, we know that along every optimal arc that hits Σ^* (starting at \( (x_0, K_0) ∈ (R_2) \) with \( x_0 ≥ x^* \)) we must have \( λ(t) < r, t ∈ (0, τ) \). In particular, \( λ(0) < r \) must hold, which is a contradiction.

Therefore, we have \( λ_0 < r \).

Since \( λ(t) < r \) for all \( t > 0 \) is not allowed, there exists \( τ > 0 \) with \( λ(τ) = r, λ(t) < r, t ∈ (0, τ) \). \( λ'(τ) = 0, z(τ) = r' \). Since the initial condition \( λ(0) = r \), is not allowed in (R2), we conclude that the trajectory must leave (R2) at some time \( σ ≤ τ \). Since there are no jumps in the interval \( (0, τ) \), the trajectory can leave (R2) only through Σ_s or Σ^*. If \( (x(σ), K(σ)) \) ∈ Σ_s we have two possibilities: i) \( σ < τ \): in this case we can find \( ε > 0 \) such that \( (x(σ + ε), K(σ + ε)) \) ∈ (R1) and \( λ(σ + ε) < r \). From item (a) above we know that this cannot occur. ii) \( σ = τ \): in this case we have \( (x(τ), K(τ)) \) ∈ Σ_s. However, this is not in agreement with the inequality \( x(τ) ≤ x^* \), which follows from \( z'(τ) = −λ''(τ) ≥ 0 \) and \( z(τ) = r' \). Therefore, the trajectory must leave (R2) through Σ^*. If \( σ < τ \), then \( λ(σ) < r \) and we have a contradiction by Lemma 14.

Thus the trajectory must leave (R2) through Σ^* at the time \( τ = r \).

To complete the proof of (b), notice that from the construction of the curves Σ_s and Σ_0 and due to the fact that \( z(τ) = r' \), \( λ(τ) = r \), we have \( z(t) > 0 \) and \( λ(t) < r \) for \( t ∈ (0, τ) \).

Ad (c): Assume \( λ(0) = r \). Then we have \( z_0 ≥ r' \). If \( z_0 = r' \), then \( λ'(0) = 0 \) and \( λ''(0) = −z'(0) = ψ_s(x_0) < 0 \). Then, there exists \( τ > 0 \) with \( λ(τ) = r, λ(t) < r, t ∈ (0, τ) \). \( λ'(τ) = 0, z(τ) = r' \). Therefore exists \( σ ∈ (0, τ) \) with \( z(σ) > r' \) and \( z'(σ) = 0 \). From the differential equation for \( z \) follows \( x(σ) > x^* \). Now, note that \( (x_0, K_0) ∈ (R_3) \) implies \( (x_0, K_{0,s}) ∈ (R_3) \) ∪ (R4); further, the solution does not jump in \( (0, σ] \) and \( u(t) = 1 \) in \( [0, σ] \). Therefore, from
Therefore, \( \rho_0 < r \). Assume \( z_0 \geq 0 \). Then \( z'(t) = zg(x) - \psi(x) > 0 \), for all \( t > 0 \) such that \( x(t) < \tilde{x} \). Consequently, \( z(t) > 0 \) as long as \( x(t) < \tilde{x} \). We already know that \( \lambda(t) < r \) as long as \( (x(t), K(t)) \in (R3) \) (i.e., no jumps in \( (R3) \)). Therefore, we conclude from the definition of \( \Gamma_2 \) that \( (x, K) \) leaves \( (R3) \) through \( \Sigma_0 \), i.e., exists \( \sigma > 0 \) with \( (x(\sigma), K(\sigma)) \in \Sigma_0 \). From the definition of \( \Sigma_0 \), follows \( x(\sigma) < \tilde{x} \). Thus, \( z(\sigma) > 0 \) must hold. Now, from \( \lambda_0 < r \), follows the existence of \( \tau > 0 \) with \( \lambda(\tau) = r \) and \( z(\tau) = r' > 0 \), \( z'(\tau) = -\lambda''(\tau) \geq 0 \) (obviously \( \tau \geq \sigma \)). Then, since \( \lambda(t) = r \) is not allowed in \( (R3) \cup \Sigma_0 \cup (R2) \), the case \( x(\tau) < x^* \) can be excluded. Therefore, \( x(\tau) = x^* \) must hold, from what follows \( (x(\tau), K(\tau)) \in \Sigma_0 \). However, this cannot occur, since \( z(\sigma) > 0 \) is not in agreement with Corollary \( 17 \).

Therefore, \( z_0 < 0 \). Note that the optimal trajectory meets \( \Sigma_0 \). Indeed, this follows from the definition of \( \Gamma_4 \) and the fact that \( \lambda(t) < r \) and \( z(t) < 0 \) as long as \( (x(t), K(t)) \in (R3) \).

\textbf{Ad (d):} The case \( \lambda_0 = r \) is excluded arguing as in \( (c) \). Assume \( z_0 > 0 \). Then \( z'(0) > 0 \) and \( z'(t) = zg(x) - \psi(x) > 0 \), for all \( t > 0 \) such that \( x(t) < \tilde{x} \). From the differential equation for \( (x, K) \), follows that the solution reaches \( (R3) \) with \( z(t) > 0 \). From item \( (c) \) we know that this is not possible. Therefore, we have \( \lambda_0 < r \) and \( z_0 < 0 \). Further, we have \( \lambda(t) < r \) and \( z(t) < 0 \) as long as \( (x(t), K(t)) \in (R4) \), since otherwise we could repeat the arguments above. From the construction of \( \Gamma_4 \), we conclude that the solution meets \( \Sigma \).

\textbf{Ad (e):} Assume \( \lambda(0) = r \). Then we have \( z_0 \geq r' \).

If \( z_0 = r' \), then \( \lambda'(0) = 0 \) and we consider three cases: \( i) \) \( x_0 > x^* \): we have \( \lambda''(0) = \psi_*(x_0) > 0 \), contradicting \( (R) \); \( ii) \) \( x_0 = x^* \): cannot occur, due to Lemma \( 9 \); \( iii) \) \( x_0 < x^* \): we have \( z'(0) > 0 \), \( \lambda''(0) < 0 \). Since \( \lambda(t) < r \) for all \( t > 0 \) is not possible, there exists \( \tau > 0 \) with \( \lambda(\tau) = r \), \( \lambda(t) < r \), \( t \in (0, \tau) \), \( \lambda'(\tau) = 0 \), \( z(\tau) = r' \).

Then there exists \( \sigma \in (0, \tau) \) with \( z'(\sigma) = 0 \), \( z(\sigma) > r' > 0 \), \( t \in (0, \sigma) \). Consequently, \( \psi_*(x(\sigma)) > 0 \) and \( x(\sigma) > x^* \). Since \( (x_0, K_0) \in (R5) \), then \( (x_0, K_0) \in (R5) \). This fact together with \( u(t) = 1 \) in \( [0, \sigma] \) and the differential equation for \( (x, K) \), implies \( K(\sigma) < F(x(\sigma))/x(\sigma) \), contradicting Lemma \( 8 \). If \( z_0 > r' \), then \( \lambda'(0) < 0 \) and we have again a contradiction.

Therefore, \( \lambda_0 < r \). Then, there exists \( \sigma > 0 \) with \( \lambda(\sigma) = r \) and \( z(\sigma) = r' > 0 \). Next we exclude two cases: \( i) \) \( z_0 < 0 \): there exists \( \sigma \in (0, \tau) \) such that \( z(\sigma) = 0 \), \( z'(\sigma) \geq 0 \) and \( z(t) < 0 \), \( t \in [0, \sigma] \). Then \( x(\sigma) \leq \tilde{x} \) must hold. However, since \( u(t) = 0 \) in \( [0, \sigma] \), we have \( x'(t) = F(x) > 0 \), \( t \in [0, \sigma] \). Thus we obtain \( x(\sigma) > x_0 > \tilde{x} \), which is a contradiction. \( ii) \) \( z_0 = 0 \): if \( z'(0) < 0 \) we obtain a contradiction arguing as in \( i) \). If \( z'(0) \geq 0 \) we have \( \psi(x_0) \leq 0 \) and \( x_0 \leq \tilde{x} \), contradicting \( (x_0, K_0) \in (R5) \).

Therefore, \( z_0 > 0 \). Finally, we prove that the optimal trajectory meets \( \tilde{\Sigma} \). We already know that \( \lambda_0 < r \). Then there exists \( \tau > 0 \) with \( \lambda(\tau) = r \) and \( z(\tau) = r' \). We consider two cases: \( i) \) \( z(\sigma) = 0 \), for some \( \sigma \in (0, \tau) \): without loss of generality, we can assume \( z'(\sigma) \leq 0 \). If \( z'(\sigma) = 0 \), then \( x(\sigma) = \tilde{x} \) and the proof is complete. If \( z'(\sigma) < 0 \), then \( x(\sigma) > \tilde{x} \) must hold. Moreover, there exists \( \rho \in (\sigma, \tau) \) with \( z(\rho) = 0 \), \( z(t) < 0 \) in \( (\sigma, \rho) \), \( z'(\rho) \geq 0 \). From \( x(\sigma) > \tilde{x} \) and \( x'(t) = F(x) > 0 \), for \( t \in (\sigma, \rho) \), follows \( x(\rho) > \tilde{x} \). But this contradicts \( x(\rho) \leq \tilde{x} \), which follows from \( z(\rho) = 0 \), \( z'(\rho) \geq 0 \). \( ii) \) \( z(t) > 0 \) in \( [0, \tau] \): since \( \lambda_0 = r \) is not allowed in \( (R5) \), the trajectory must leave \( (R5) \) at some time \( \sigma \leq \tau \). From \( \lambda(t) < r \) in \( [0, \sigma] \) (i.e., no jumps in \( [0, \sigma] \)), \( u(t) = 1 \) in \( [0, \sigma] \) and the differential equation for \( (x, K) \), we conclude that the trajectory must leave \( (R5) \) through \( \tilde{\Sigma} \) as conjectured.

Theorem 28 Let \((x, K, u, \mu)\) be optimal with adjoint variables \( z, \lambda \). The following assertions hold:
5 Appendix: maximum principle

Theorem 29 Let \((x, K, u, \mu)\) be optimal with adjoint variables \(z, \lambda\). The following assertions hold:

(a) Let \((x_0, K_0)\) be on \(\Sigma^*\). Then \(z_0 = r', \lambda = r, (x_0, K_0, \mu) = (x^*, K^*)\) and \(u \equiv 1, \mu = \gamma K dt\);

(b) Let \((x_0, K_0)\) be on \(\Sigma_0\). Then \(z_0 = 0, \lambda_0 < r\) and there exists \(\tau > 0\) with \((x(\tau), K(\tau)) \in \Sigma^*\) and \(u \equiv 1, \mu \equiv 0\) in \((0, \tau)\);

(c) Let \((x_0, K_0)\) be on \(\Sigma\). Then \(z_0 = 0, \lambda_0 < r\) and there exists \(\tau_1 > 0, \tau_2 > \tau_1\) with \((x(\tau_1), K(\tau_1)) = (0, \tilde{K}), (x(\tau_2), K(\tau_2)) \in \Sigma^*\). Moreover

\[
\mu_{1|0,\tau_1} \equiv 0, \quad u(t) = K(t)^{-1}F(\tilde{x})\tilde{x}^{-1}, \quad t \in (0, \tau_1), \quad \mu_{1|\tau_1,\tau_2} \equiv 0, \quad u_{1|\tau_1,\tau_2} \equiv 1.
\]

Proof: Note that (a) was already proved in Lemma 11. Item (b) is proved exactly in the same way as Theorem 27(b). Now we prove (c).

Assume \(\lambda(0) = r\). Then \(z_0 \geq r'\). If \(z_0 = r'\), then \(\lambda'(0) = 0, \lambda''(0) = -\psi'(\tilde{x}) > 0, \lambda'''(0) = -\psi''(\tilde{x}) > 0, \lambda''''(0) = -\psi'''(\tilde{x}) > 0\). If \(z_0 > r'\), then \(\lambda'(0) < 0\). In each case there exists \(\tau > 0\) with \(\lambda(\tau) = r, \lambda(t) < r\), \(t \in (0, \tau)\), and we obtain \(\lambda'(\tau) = 0, z(\tau) = r'\) and \(\sigma \in (0, \tau)\) with \(z'(\sigma) = 0\). Moreover \(\lambda(t) < r\), \(t \in (0, \tau)\), \(z(t) > r', t \in (0, \tau)\). Thus we arrive in (R5) with \(z(t) > 0, \lambda(t) < r\). But this is not in agreement with the results for domain (R4). Therefore, \(\lambda_0 < r\) must hold.

If \(z_0 < 0\), then the trajectory meets (R5) with \(z(t) < 0, \lambda(t) < r\), which is not possible due to the results for (R5). If \(\lambda_0 < r\) and \(z_0 > 0\), the trajectory reaches (R4) with \(z(t) > 0, \lambda(t) < r\), but this is not allowed due the results for (R4).

Thus we have \(\lambda_0 < r, z_0 = 0\) and, consequently, \(z'(0) = 0\). Repeating the arguments above, we conclude that the trajectory cannot leave \(\Sigma \) as long as \(K(t) \geq \tilde{K}\) holds. Therefore, there exists \(\tau_1 > 0\) with \(x(t) = \tilde{x}, u(t) = F(\tilde{x})\tilde{x}^{-1}K(t)^{-1}, t \in [0, \tau_1]\). In \((\tilde{x}, \tilde{K})\) the trajectory has to follow \(\Gamma_2\), otherwise it would enter (R2) strictly above \(\Gamma_2\) and below \(\Gamma_3\) with \(z \leq 0\) which is not allowed due to Theorem 27(b). Thus the trajectory meets \(\Sigma^*\) at a time \(\tau_2 > \tau_1 > 0\).

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Minimize \( J(x_0, K_0; \mu, u) := \int_0^\infty e^{-\delta t} r \mu(dt) + \int_0^\infty e^{-\delta t} \{c - px(t)\} u(t)K(t)dt \)
subject to \((u, \mu) \in U_{ad} \times C^*\) and
\[
\begin{align*}
x' &= F(x) - u(t)Kx, \quad x(0) = x_0, \\
dK &= -\gamma K dt + \mu(dt), \quad K(0) = K_0,
\end{align*}
\]
where
\[
U_{ad} := \{v \in L_\infty[0, \infty) \mid 0 \leq v(t) \leq 1 \text{ a.e. in } [0, \infty]\},
\]
\[
C^* := \{\mu \mid \mu \text{ non-negative Borel measure on } [0, \infty]\}.
\]
This problem is denoted by \( P(x_0, K_0) \). Let \((x, K, u, \mu)\) be a solution of the problem. The idea for proving a maximum principle comes from [7] and [17]. Halkin, however, uses a different solution concept, avoiding the use of Bellman’s principle to analyze problems with infinite horizon.

Define the so-called Hamilton function \( \tilde{H} \) by
\[
\tilde{H}(t, \tilde{x}, \tilde{K}, w, \tilde{\lambda}_1, \tilde{\lambda}_2, \eta) := \tilde{\lambda}_1(F(\tilde{x}) - w\tilde{K}\tilde{x}) - \tilde{\lambda}_2\gamma K - \eta e^{-\delta t}(c - px)wK.
\]
Let \((T_k)_{k \in \mathbb{N}}\) be a sequence in \((0, \infty)\) with \(\lim_k T_k = \infty\) and consider for each \(k \in \mathbb{N}\) the following problem \( P_k(x_0, K_0) \):

Minimize \( J(x_0, K_0; \nu, w) := \int_0^{T_k} e^{-\delta t} r \nu(dt) + \int_0^{T_k} e^{-\delta t} \{c - py(t)\} w(t)l(t)dt \)
subject to \((w, \nu) \in U_{ad,k} \times C_k^*\) and
\[
\begin{align*}
y' &= F(y) - w(t)l y, \quad y(0) = x_0, \quad y(T_k) = x(T_k), \\
dl &= -\gamma l dt + \nu(dt), \quad l(0) = K_0, \quad l(T_k) = K(T_k),
\end{align*}
\]
where
\[
U_{ad,k} := \{v \in L_\infty[0, T_k] \mid 0 \leq v(t) \leq 1 \text{ a.e. in } [0, T_k]\},
\]
\[
C_k^* := \{\mu \mid \mu \text{ nonnegative Borel measure on } [0, T_k]\}.
\]
**Assumption:** \( T_k \) is a point of continuity for each \( k \in \mathbb{N} \). (Clearly such a choice of \((T_k)_{k \in \mathbb{N}}\) is always possible since \( K \) possesses only a countable number of jumps.)

Once one has proved the Bellman’s optimality principle for control problems with infinite horizon (see [2]), one concludes that for each \( k \in \mathbb{N} \), \((x[0,T_k], K[0,T_k], \mu[0,T_k], u[0,T_k])\) is a solution of \( P_k(x_0, K_0) \). With the maximum principle proved in [19], we obtain \( \lambda_{1,k}, \lambda_{2,k}, \eta_k \in \mathbb{R} \) such that there exists \( \lambda_{1,k}, \lambda_{2,k} \) with
\[
\begin{align*}
\tilde{\lambda}_{1,0,k}^2 + \tilde{\lambda}_{2,0,k}^2 + \eta_k^2 &= 1, \quad \eta_k \geq 0, \\
x' &= F(x) - u(t)Kx, \quad x(0) = x_0, \\
dK &= -\gamma K dt + \mu(dt), \quad K(0) = K_0, \\
\tilde{\lambda}_{1,k} &= -\tilde{\lambda}_{1,k}(F'(x) - u(t)K) - \eta_k e^{-\delta t} pu(t)K, \\
\tilde{\lambda}_{2,k} &= \tilde{\lambda}_{1,k} xu + \lambda \tilde{\lambda}_{2,k} + \eta_k e^{-\delta t}(c - px)u(t), \\
\tilde{\lambda}_{2,k}(t) - \eta_k e^{-\delta t} r &= 0 \text{ for all } t \in [0, T_k], \\
\tilde{\lambda}_{1,k}(0) &= \tilde{\lambda}_{1,0,k}, \quad \tilde{\lambda}_{2,k}(0) = \tilde{\lambda}_{2,0,k}, \\
\tilde{\lambda}_{2,k}(t) - \eta_k e^{-\delta t} r &= 0 \mu-a.e. \text{ in } [0, T_k],
\end{align*}
\]
\[
\tilde{H}(t, x(t), K(t), u(t), \tilde{\lambda}_{1,k}(t), \tilde{\lambda}_{2,k}(t), \eta_k) = \max_{w \in [0,1]} \tilde{H}(t, x(t), K(t), w, \tilde{\lambda}_{1,k}(t), \tilde{\lambda}_{2,k}(t), \eta_k)
\]
a.e. in \([0, T_k]\).
Without loss of generality we may assume that the sequences \((\tilde{\lambda}_{1,0,k}, \tilde{\lambda}_{2,0,k})_{k \in \mathbb{N}}\) and \((\eta_k)_{k \in \mathbb{N}}\) converge. Let
\[
\tilde{\lambda}_{1,0} := \lim_{k \to \infty} \tilde{\lambda}_{1,0,k}, \quad \tilde{\lambda}_{2,0} := \lim_{k \to \infty} \tilde{\lambda}_{2,0,k}, \quad \eta := \lim_{k \to \infty} \eta_k.
\]
Then, due to the continuous dependence of the solution on initial data and parameter (see [11]) we obtain
\[
\tilde{\lambda}_1 := \lim_{k \to \infty} \tilde{\lambda}_{1,k}, \quad \tilde{\lambda}_2 := \lim_{k \to \infty} \tilde{\lambda}_{2,k},
\]
uniformly on each interval \([0,T], T > 0\). This gives the desired maximum principle for \(P(x_0, K_0)\):

There exist \(\tilde{\lambda}_{1,0}, \tilde{\lambda}_{2,0}, \eta \in \mathbb{R}\) such that there exists \(\tilde{\lambda}_1, \tilde{\lambda}_2\) with
\[
\tilde{\lambda}_{1,0}^2 + \tilde{\lambda}_{2,0}^2 + \eta^2 \neq 0, \quad \eta \geq 0,
\]
\[
x' = F(x) - u(t)Kx, \quad x(0) = x_0,
\]
\[
dK = -\gamma dK + \mu(dt), \quad K(0) = K_0,
\]
\[
\tilde{\lambda}_1 = -\tilde{\lambda}_1 F'(x) - u(t)K - \eta e^{-\delta t} pu(t) K,
\]
\[
\tilde{\lambda}_2 = \tilde{\lambda}_1 xu + \gamma \tilde{\lambda}_2 + \eta e^{-\delta t} (x - px) u(t),
\]
\[
\tilde{\lambda}_1(0) = \tilde{\lambda}_{1,0}, \quad \tilde{\lambda}_2(0) = \tilde{\lambda}_{2,0},
\]
\[
\tilde{\lambda}_2(t) - \eta e^{-\delta t} \leq 0 \text{ for all } t \in [0, \infty),
\]
\[
\tilde{\lambda}_2(t) - \eta e^{-\delta t} = 0 \mu \text{-a.e. in } [0, \infty),
\]
\[
\tilde{H}(t, x(t), K(t), u(t), \tilde{\lambda}_1(t), \tilde{\lambda}_2(t), \eta) = \max_{w \in [0,1]} \tilde{H}(t, x(t), K(t), w, \tilde{\lambda}_1(t), \tilde{\lambda}_2(t), \eta) \text{ a.e. in } [0, \infty).
\]

References

[1] Anderson, L.G., The Economics of Fishery Managements, The Hopkins University Press, Baltimore, 1986.

[2] Baumeister, J., Leitao, A.G., Silva, G.N., Optimal control problems with infinite horizon whose control laws contain measures: Maximum principle, Nonlinear dynamics, chaos, control, and their applications to engineering sciences, 4, 228–250 (2002)

[3] Clark, C.W., Mathematical Bioeconomics (second edition), Wiley, 1990.

[4] Clark, C.W., Clarke, F.H., Munro, G.R., The optimal exploitation of renewable resource stocks, Econometrica 47, 25 – 47 (1979)

[5] Dal Maso, G., Rampazzo, F., On systems of ordinary differential equations with measures and controls, Differ. Integr. Eq., 4, 739 – 765 (1991)

[6] Flaaten, O., The Economics of Multispecies Harvesting, Springer–Verlag, Berlin, 1988.

[7] Halkin, H., Necessary conditions for optimal control problems with infinite horizon, Econometrica, 42, 267 – 272 (1974)

[8] Motta, M., Rampazzo, F., Dynamic programming for nonlinear systems driven by ordinary and impulsive controls, SIAM J. Contr. Optim., 34, 199 – 225 (1996)

[9] Murray, J.M., Existence theorems for optimal control and calculus of variations problems where the state can jump, SIAM J. Control and Optimization, 24, 412 – 438 (1986)
[10] Rischel, R.W., An extended Pontryagin principle form control systems whose control laws contain measures, SIAM J. Control and Optimization, 3, 191 – 205 (1965)

[11] Schmaedecke, W.W., Optimal control theory for nonlinear vector differential equations containing measures, SIAM J. Control, 3, 231 – 280 (1965)

[12] Seierstad, A., Sydsaetter, K., Optimal Control Theory with Economic Applications, North–Holland, Amsterdam, 1987.

[13] Sieveking, M., Existenz bei Steuerungsproblemen mit unendlichem Horizont, Fachbereich Mathematik der J. W. Goethe–Universität; Private communication, 1998.

[14] Silva, G.N., Rowland, J.D., On the optimal impulsive control problem, Rev. Mat. Estat., 14, 17–33 (1996)

[15] Silva, G.N., Vinter, R.B., Necessary conditions for optimal impulsive control problems, SIAM J. Control Optim., 35, 1829 – 1846 (1997)

[16] Vinter, R.B., Pereira, F.M., A maximum principle for optimal processes with discontinuous trajectories, SIAM J. Control and Optimization, 26, 205 – 229 (1988)

[17] Werner, C., Der kürzeste Weg zum Gleichgewicht als Steuerungsprinzip – Ein Gegenbeispiel, Diplomarbeit, Fachbereich Mathematik der J. W. Goethe–Universität, 1996.
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Figure 1: Curves $\Gamma_1$ and $\Sigma^*$. 

Figure 2: Curve $\Sigma_0$. 

$K = \frac{F(x)}{x}$
Figure 3: Main curves.

Figure 4: Main regions.