



HAL
open science

Optimal growth models under Rawlsian criteria

Stefano Bosi, Thai Ha-Huy

► **To cite this version:**

| Stefano Bosi, Thai Ha-Huy. Optimal growth models under Rawlsian criteria. 2024. <hal-04481516v3>

HAL Id: hal-04481516

<https://hal.science/hal-04481516v3>

Preprint submitted on 18 Mar 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



OPTIMAL GROWTH MODELS UNDER RAWLSIAN CRITERIA

STEFANO BOSI^{1,*}, THAI HA-HUY^{1,2}

¹ Université Paris-Saclay, Univ Evry, CEPS, bd F. Mitterrand, 91025, Evry-Courcouronnes, France

² University Thang Long, TIMAS, Vietnam

Dedicated to the memory of Tapan Mitra, a leading economist and an example to us all.

Abstract. This article revisits the optimal growth with three distinct Rawlsian approaches: (1) the original Rawlsian criterion, popular in economic literature; (2) the maximin with multiple discount factors, introduced by [8]; (3) the rank-dependent criterion, applied by [27] to growth theory. Finally, we develop a new approach based on a convex combination of the most common criteria: Ramsey-Cass-Koopmans and Rawls.

Keywords. Maximin principle; Multiple discount rates; Ramsey-Cass-Koopmans models; Rawls criterion.

2020 MSC. 91B62.

1. INTRODUCTION

Fundamental questions in economic growth theory are how to define a criterion reconciling efficiency and equality, and how to compute the economy behavior under this criterion.

The most popular utilitarian approach to growth theory is the Ramsey-Cass-Koopmans criterion (hereinafter RCK). The main criticism addressed to this criterion is the unequal treatment between close and distant future. In fact, given an intertemporal utility stream, its value is computed weighting less the future generations. This leads to a situation where the current generation does not leave enough resource to the future ones. In his seminal contribution, [24] considers that discounting the welfare of future generations is “ethically indefensible and arises merely from the weakness of the imagination.”¹

[25] argues that, behind the “veil of ignorance”, the economic agent must adopt the criterion which maximizes the welfare of the least generation. How the economy behaves under this criterion is an important question. [3], [7] and [23] address this issue in different contexts such as constant productivity or uncertain technology and come to the pessimistic conclusion that, if

*Corresponding author.

E-mail address: stefano.bosi@univ-evry.fr (S. Bosi).

Received May 8, 2024; Accepted July 1, 2024.

¹See also [27] for a review.

the economy starts with a low stock of capital, in order to preserve intergenerational equality, any generation must remain at this poor level.

[14] extends the *maximin* criterion with multiple discounting in [8] to defines a new Rawls-like criterion. He argues that, behind the “veil of ignorance”, the economic agent faces the ambiguity about the appropriate discount factor to evaluate the intertemporal utility stream. In this case, given an intertemporal utility stream (u_0, u_1, \dots) , the criterion becomes

$$\inf_{\delta \in (0,1)} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u_t.$$

[14] shows that, under this criterion, the economy behaves as under the Rawlsian one.

Criteria preserving equality present another difficulty. [11] and [6] proved that there is no function representing a criterion which satisfies both *Pareto*² and *anonymity*³ properties. In other words, it is difficult to reconcile efficiency and equality.

The *overtaking* criterion by [13] seems to overcome this difficulty, since it is both Paretian and anonymous. The future generations are not discounted. However, preferences represented by the *overtaking* criterion are not complete. Moreover, when the economy starts with a low initial stock of capital, the criteria that don't discount the future, ask the first generations to sacrifice.⁴

[27] applies the *rank-dependent* method of social welfare theory to growth theory. They interpret the discount factor as a way to avoid sacrifices of poor generations too harsh. The key idea is weighting more the worst generations in the intertemporal evaluation. They first provide an axiomatic foundation to this new criterion by applying the axioms introduced by [17, 18], such as separability between present and future, stationarity and the Paretian property, to the set of utility streams either increasing or *rearrangeable as increasing* instead of to the whole set of streams. In this respect, the evaluation of a stream (u_0, u_1, \dots) can be reformulated as:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u_{\pi(t)},$$

where Π represents the set of all possible permutations of natural numbers $N \equiv \{0, 1, \dots\}$ and $\delta \in (0, 1)$ is a discount factor.

[27] apply this criterion to growth theory and prove that, in this case, the solution coincides with the optimal path of the Rawlsian criterion when the productivity is low, and with the optimal path of the Ramsey-Cass-Koopmans model when the productivity is high.⁵

An added value of our article is the global analysis of growth trajectories under the [27] criterion.⁶ Starting with a capital stock below the *modified golden rule*, the economy follows the same trajectory as in the RCK model: the consumption increases over time and converges to the level of *modified golden rule*. If the initial capital stock is between the *modified golden rule* and the *golden rule*, then it remains constant forever and equal to its initial value. Finally,

² Increasing the welfare of one generation in keeping unchanged the others increases the evaluation of intertemporal utility sequence.

³Permuting the utility level of different generations does not change the evaluation of the intertemporal utility stream.

⁴[21] shows that the first generations' saving rate may go up to more than 50%.

⁵See Proposition 10 in [27].

⁶The *golden rule* capital stock maximizes the stationary consumption level. The *modified golden rule* is the steady state under the utilitarian criterion in the RCK model.

if the initial capital stock is larger than the *golden rule*, then there are infinitely many optimal paths, all converging to the *golden rule*.

An additional added value, is the definition of new criteria balancing efficiency and equality. [1] in continuous time and [15] in discrete time study weighted sums of RCK and Rawlsian criteria.⁷ Both these contributions share the same idea: a Rawlsian criterion, stressing the equality between generations, tends to promote forever a state of the economy with low capital. Could we weaken the equality degree to ensure more future development? To this purpose, to what extent we have to sacrifice the equality principle? These contributions prove that, starting with a low level of capital, the economy follows the RCK optimal path in the long run, while with a high level, it converges to a RCK-like steady state which is a modified *modified golden rule* corresponding to a higher discount factor.

In our paper, we also consider a weighted sum of RCK criterion and [27]. If the initial capital stock is low, then the optimal path coincides with the optimal RCK trajectory. Otherwise, the optimal path coincides with the trajectory under the criterion in [14] and it converges to a higher steady state.

The article is organized as follows. In Section 2, we present three Rawlsian criteria and an equivalence result between the first two. Section 3 provides a global analysis of trajectories under the criterion in [27] and a weighted sum of RCK and [27].

2. THREE RAWLSIAN CRITERIA

2.1. Fundamentals. Time is discrete: $t = 0, 1, \dots$. At time t , given the stock of capital $x_t \geq 0$, the production level is $f(x_t)$. The economic agent, which can be interpreted as a sequence of successive generations, divides this output into consumption c_t and capital investment for tomorrow, $x_{t+1} \geq 0$. Given the consumption c_t , the utility level at time t is $u(c_t)$. We assume that the production function f is concave and satisfies the Inada conditions: $f'(0) = \infty$ and $f'(\infty) < 1$. The utility function u is strictly increasing and strictly concave.

Let $x_0 > 0$ be a given capital stock and $\Phi(x_0)$ the set of feasible sequences $\chi = (x_t)_{t=0}^{\infty}$ with $0 \leq x_{t+1} \leq f(x_t)$ for any $t \geq 0$. Denote by Π the set of every possible permutations of natural numbers $\mathbb{N} \equiv \{0, 1, \dots\}$.

Let \bar{x} be the *golden rule*, maximizing the constant consumption $f(\bar{x}) - \bar{x}$, solution to $f'(x) = 1$. Given the discount factor $\delta \in (0, 1)$, let x^* be the corresponding *modified golden rule*, the steady state of the RCK problem, solution to $\delta f'(x) = 1$.

The economic agent maximizes the intertemporal utility $U(c_0, c_1, \dots)$ to smooth her consumption over time. More precisely, given the initial capital stock x_0 , she solves the following program:

$$\begin{aligned} v(x_0) &= \max U(c_0, c_1, \dots), \\ c_t + x_{t+1} &\leq f(x_t), \\ c_t, x_{t+1} &\geq 0, \end{aligned}$$

for any $t \geq 0$, given $x_0 > 0$. The function v is called the value of the optimization program.

⁷In a purpose of balancing close and distant futures, [9, 10] proposes *non-dictatorship* properties. These criteria have inspired many works thereafter. However, as pointed out by [16], under the assumption *non-dictatorship* there is no optimal path in models with renewable resources. A similar result holds in an optimal growth context (see [5]). [4] and [12] try to find more satisfactory solutions with alternative approaches.

(1) The criterion of [25] focuses on the welfare of the worst generation. More precisely, given a consumption sequence (c_0, c_1, \dots) , the evaluation of the intertemporal utility stream is given by

$$U(c_0, c_1, \dots) = \inf_{t \geq 0} u(c_t).$$

(2) [14] considers the alternative maximin criterion with multiple discounting introduced by [8]. Behind the Rawlsian “veil of ignorance”, the economic agent does not know the right discount factor to apply in order to evaluate the utility stream. In this respect, she is in a total ambiguous situation.

The maximin approach leads to a second Rawlsian criterion:

$$U(c_0, c_1, \dots) = \inf_{\delta \in (0,1)} \left[\sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) \right],$$

where the argument in the RHS is an arithmetic average with geometric weights $(1 - \delta) \delta^t$. The second Rawlsian criterion can be also reinterpreted as an application of the first one to a population with heterogenous discounting and the set of discount factors spanning from 0 to 1. The welfare of each population member is the intertemporal sum using her own δ . The planner maximizes the welfare of the worst agent in the population.

(3) In [27], the discount factor is necessary only to prevent hard sacrifices of the worst generations. In this respect, they reconsider the *rank-dependent* method well-known in social welfare literature from a dynamic perspective. More precisely, they apply the axiomatic system elaborated by [17, 18] to increasing utility streams or to streams that can be rearranged as increasing. In doing so, they introduce a third Rawlsian criterion:

$$U(c_0, c_1, \dots) = \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}),$$

or, equivalently,

$$U(c_0, c_1, \dots) = \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}), \quad (2.1)$$

where Π represents the set of all permutations in the set of natural numbers \mathbb{N} and δ is a given discount factor in $(0, 1)$. The third Rawlsian criterion weights more the worst generations.

Since the main purpose of this article is to study the properties of optimal growth under different Rawlsian criteria, we need to demonstrate the existence of an optimal path, without which all results would be in vain. However, in order to keep things as simple as possible, we assume this to be the case, while inviting interested readers to refer to the set of sufficient conditions provided by [20] (Hypothesis H1 to H6). Among them, *tail-insensitivity* plays the key role by entailing the continuity of the intertemporal utility function for the product topology and, hence, the continuity of the value function in the initial capital stock. Under these assumptions, for each Rawlsian criterion presented in this article, an optimal capital accumulation path always exists.

2.2. The first two Rawlsian criteria. The first Rawlsian criterion is studied in a series of contributions, such as [2, 3], [7], [23] among others. The second one is applied in an optimal growth context by [14].

(1) Let us present shortly the dynamic properties of the economy under the first Rawlsian criterion.

(1.1) If $0 \leq x_0 \leq \bar{x}$, then for any feasible path $\chi \in \Phi(x_0)$, we have

$$\inf_{t \geq 0} u(f(x_t) - x_{t+1}) \leq u(f(x_0) - x_0).$$

The equality holds if and only if $x_t = x_0$ for every $t \geq 0$. Then the optimal sequence is (x_0, x_0, \dots) .

(1.2) In the case $x_0 > \bar{x}$, we have

$$\inf_{t \geq 0} u(f(x_t) - x_{t+1}) \leq u(f(\bar{x}) - \bar{x}). \quad (2.2)$$

There is an infinite number of optimal sequences (x_0, x_1, \dots) such that (2.2) holds with equality. They are all decreasing and converge to \bar{x} .

(2) Under the second Rawlsian criterion, the optimal path has the same qualitative properties.

(2.1) If $0 \leq x_0 \leq \bar{x}$, the unique optimal path is the initial condition forever: (x_0, x_0, \dots) (see Corollary 2.1 in [14]). The value function becomes $v(x_0) = u(f(x_0) - x_0)$.

(2.2) If $x_0 > \bar{x}$, then any optimal path under the first Rawlsian criterion is also an optimal path under the second one. Any optimal path is decreasing and converge to \bar{x} (see Corollary 2.1 in [14]). The value function is $v(x_0) = u(f(\bar{x}) - \bar{x})$.

We observe that, though these two criteria are different, they lead to the same optimal path and the same value function. Starting from a low capital stock, the economy remains poor forever.

2.3. The third Rawlsian criterion. Focus on the third Rawlsian criterion (2.1). Consider the following optimization problem:

$$v(x_0) = \max_{\chi \in \Phi(x_0)} \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}) - x_{\pi(t)+1}).$$

The next lemma states some fundamental properties. If the consumption sequence is increasing, the third criterion and the utilitarian criterion (RCK) result in the same evaluation with larger weights on poorer generations. In the general case, the evaluation under the third criterion is bounded from above by the limit infimum of the utility sequence, normalized by $1 - \delta$.

Lemma 2.1. *Consider a consumption sequence (c_0, c_1, \dots) .*

(1) *If the sequence (c_0, c_1, \dots) is non-decreasing, then*

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) = \sum_{t=0}^{\infty} \delta^t u(c_t). \quad (2.3)$$

(2) *If there exists infinitely many t such that $u(c_t) \leq w + (1 - \delta)\varepsilon$ for some utility level w and any $\varepsilon > 0$, then*

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) \leq \frac{w}{1 - \delta}.$$

(3) If there exist infinitely many t such that $u(c_t) \leq w + (1 - \delta)\varepsilon$ for any $\varepsilon > 0$ and there exists τ such $u(c_\tau) < w$, then the inequality in part (2) becomes strict:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) < \frac{w}{1 - \delta}.$$

Using results in Lemma 2.1, we can prove the next proposition describing the optimal path under the third criterion. When the economy starts with a low capital stock, $x_0 \leq x^*$, where x^* is the solution to $\delta f'(x) = 1$ (*modified golden rule*), then it follows the same path we obtain under the RCK criterion. When the economy starts from an intermediate level, $x^* \leq x_0 \leq \bar{x}$, then its capital level remains constant forever. If the initial capital stock is large enough ($x_0 \geq \bar{x}$), then the set of solutions under the third criterion coincides exactly with the set of solutions under the first criterion. Every optimal path is decreasing and converges to the *golden rule*.

Proposition 2.2. Consider an optimal path χ^* under the third Rawlsian criterion.

(1) If $x_0 \leq x^*$, then χ^* is also the solution under RCK criterion. This is an increasing sequence converging to x^* . The value of this problem is the same of the RCK program. If f and u are strictly concave, then this optimal path is unique.

(2) If $x^* < x_0 \leq \bar{x}$, the optimal path is $\chi^* = (x_0, x_0, \dots)$ and the value of (2.1) is given by

$$v(x_0) = \frac{u(f(x_0) - x_0)}{1 - \delta}.$$

(3) If $x_0 > \bar{x}$, there exists an infinite number of solutions, all converging to \bar{x} , and the value is given by

$$v(x_0) = \frac{u(f(\bar{x}) - \bar{x})}{1 - \delta}.$$

3. THE EFFICIENCY-EQUALITY BALANCE

Any criterion treating all generations equally satisfies the *anonymity* property, ensuring that the evaluation of an intertemporal utility stream does not change after a permutation of welfare level of different generations. However, [11] and [6] have shown that these criteria can not be represented by a function satisfying also the *Pareto* property.

[1] in continuous time and [15] in discrete time consider a weighted sum of two criteria: RCK and the first Rawls. In our notation, we have

$$U(c_0, c_1, \dots) = \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + a \inf_{t \geq 0} u(c_t). \quad (3.1)$$

Parameter $a \geq 0$ represents the equality degree in this hybrid criterion. As limit cases, if $a = 0$, we recover the standard RCK criterion and, if a converges to infinity, we have the first Rawlsian one.

The results concerning the qualitative properties of the optimal path can be organized into two parts.

(1) When the initial capital is low, $x_0 \leq x^*$, where x^* is the *modified golden rule*, then its stock slowly increases in the period of life of the first generations. However, in the long run, the trajectory of the capital stock will approach and, from a critical date on, coincides with the RCK

optimal path.⁸ The equality parameter a in the hybrid criterion reduces the distance in terms of utility between the generations with the highest and lowest utility levels.

(2) The case $x_0 > x^*$ is more complicated to handle. Two critical levels matter: $0 \leq a_1 \leq a_2$ with $a_2 > 0$.

(2.1) If $0 \leq a \leq a_1$, the equality part plays no role and the optimal path coincides with the one under the RCK criterion (see part (iii) of Proposition 2.2 in [15]).

(2.2) When $a_1 < a < a_2$, the economy converges to the *modified golden rule* as in the RCK model, but with a larger discount factor $\tilde{\delta} > \delta$ (see part (i) of Proposition 2.2 in [15]).

(2.3) If $a \geq a_2$, the equality part fully dominates and we recover the optimal path of the first Rawlsian criterion (see part (ii) of Proposition 2.2 in [15]).

We see that the equality degree a increases the welfare of generations living in a far future with respect to their level under the standard utilitarian criterion. It is easy to see that the criteria represented by (3.1) and

$$U(c_0, c_1, \dots) = (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{t \geq 0} u(c_t),$$

with $\lambda = a/(1 + a)$ are equivalent.

Along similar lines, we define a new hybrid criterion which combines a standard utilitarian part with an equality part, and we study the optimization problem under the weighted sum of RCK and [27]. More precisely, we introduce the Ramsey-Zuber-Asheim (RZA) criterion as follows:

$$U(c_0, c_1, \dots) = (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}),$$

where the parameter $\lambda \in [0, 1]$ represents the equality degree in the new criterion. When $\lambda = 0$, we recover the standard RCK criterion, while, when $\lambda = 1$, the third Rawlsian criterion, considered in subsection 2.3.

There are two cases.

(1) When the initial capital is low, $x_0 \leq x^*$, the optimal path is the solution under the RCK criterion. Therefore, if the economy starts with a low stock of capital, this criterion promotes development differently from the first Rawlsian criterion.

(2) When $x_0 > x^*$, we prove that the optimal accumulation coincides with the capital path under the hybrid criterion, which is a weighted sum between RCK and the first Rawlsian criterion, applied in [15]. Hence, for a sufficiently large equality degree λ , the economy converges in the long run to the *modified golden rule* as in the RCK model, but with a larger discount factor (the reader is still referred to Proposition 2.2 in [15]).

These results are formalized and summarized in the next and last proposition.

Proposition 3.1. *Let $0 < \lambda < 1$.*

(1) *If the economy starts with $0 < x_0 \leq x^*$, then the optimal path under RZA criterion coincides with the one under the RCK criterion.*

(2) *If the economy starts with $x_0 > x^*$, then there are two critical values with $0 < \lambda_1 < \lambda_2 < 1$ such that:*

⁸See Proposition 2.1 in [15].

(2.1) If $0 < \lambda \leq \lambda_1$, the equality part plays no role, and the optimal path under the RZA criterion is also the one under the RCK criterion, converging to x^* .

(2.2) If $\lambda_1 < \lambda < \lambda_2$, then the optimal path under the RZA criterion is decreasing and converges to a steady state corresponding to a discount rate $\tilde{\delta}$ greater than δ .

(2.3) If $\lambda \geq \lambda_2$, then the optimal path under the RZA criterion follows the optimal path of the first Rawlsian criterion.

4. CONCLUSION

In this article, we considered the behavior of the economy under different Rawlsian criteria and the weighted sum of the popular utilitarian RCK with these criteria. We obtained the optimal solutions from the planner's viewpoint.

A number of questions remain unanswered. In the context of these criteria, how does productivity (TFP) influence the optimal trajectory? What should the competitive equilibria be? Could fiscal policy implement the optimal trajectories described in our article?

Let us conclude by remarking that, if we replace the weighted sum of RKC and a Rawlsian criterion with a new criterion as a strictly increasing function of the standard utilitarian value and the equality value, the qualitative behavior of the economy does not change. However, the shape of the function would affect the optimal degree of equality, that is the efficient sacrifice in terms of equality.

5. APPENDIX

Proof of Lemma 2.1

(1) Let π^* the permutation such that $\pi^*(t) = t$ for every t . Since this permutation weights more the lower utility levels, equation (2.3) follows.

(2) Fix $\varepsilon > 0$. Denote by $(t_n)_{n=0}^{\infty}$ the subsequence of $(m)_{m=0}^{\infty}$ such that $u(c_{t_n}) \leq w + (1 - \delta)\varepsilon$. Since the sequence (c_0, c_1, \dots) is bounded from above, we can fix N sufficiently large such that for any $\pi \in \Pi$, we have $\sum_{t=N+1}^{\infty} \delta^s u(c_{\pi(t)}) < \varepsilon$.

Consider a permutation π^* such that $\pi^*(n) = t_n$ for any $n \in \{0, 1, \dots, N\}$. We have

$$\begin{aligned} \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^s u(c_{\pi(t)}) &\leq \sum_{t=0}^{\infty} \delta^s u(c_{\pi^*(t)}) = \sum_{t=0}^N \delta^s u(c_{t_n}) + \sum_{t=N+1}^{\infty} \delta^s u(c_{\pi^*(t)}) \\ &\leq [w + (1 - \delta)\varepsilon] \sum_{t=0}^N \delta^s + \varepsilon. \end{aligned}$$

Let N converge to infinity. Then

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^s u(c_{\pi(t)}) \leq \frac{w}{1 - \delta} + 2\varepsilon.$$

Since ε is arbitrary, we have

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^s u(c_{\pi(t)}) \leq \frac{w}{1 - \delta}.$$

(3) Choose a permutation π^* such that $\pi^*(0) = \tau$, and $\pi^*(n) = t_n$ for each $n \in \{0, 1, \dots, N\}$ where N is defined as in the proof of part (2). Then

$$\begin{aligned} \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) &\leq \sum_{t=0}^{\infty} \delta^t u(c_{\pi^*(t)}) \\ &= u(c_{\tau}) + \sum_{t=1}^N \delta^t u(c_{t_n}) + \sum_{t=N+1}^{\infty} \delta^t u(c_{\pi^*(t)}) \\ &\leq u(c_{\tau}) + [w + (1 - \delta)\varepsilon] \sum_{t=1}^N \delta^t + \varepsilon. \end{aligned}$$

Since the inequality is satisfied for any N large enough, we can let N converge to infinity to obtain

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) \leq u(c_{\tau}) + \frac{\delta w}{1 - \delta} + (1 + \delta)\varepsilon.$$

Since ε is arbitrary, recalling that $u(c_{\tau}) < w$, we obtain the following inequality:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(c_{\pi(t)}) \leq u(c_{\tau}) + \frac{\delta w}{1 - \delta} < \frac{w}{1 - \delta}.$$

Proof of Proposition 2.2

For simplicity, with a notational misuse, let us denote

$$U(\chi) \equiv \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}) - x_{\pi(t)+1}),$$

for any feasible sequence $\chi \in \Phi(x_0)$.

(1) Let $x_0 \leq x^*$. Let χ be the optimal path of the program under the RCK criterion. One of the well-known results in dynamic programming literature is that $(u(f(x_t) - x_{t+1}))_{t=0}^{\infty}$ is non-decreasing.⁹ Part (1) of Lemma 2.1 applies and the claim is proven.

(2) The most challenging case is $x^* < x_0 \leq \bar{x}$. We know that, since $x_0 \leq \bar{x}$,

$$\max_{\chi \in \Phi(x_0)} \inf_{t \geq 0} u(f(x_t) - x_{t+1}) = u(f(x_0) - x_0),$$

with unique solution $\chi^* = (x_0, x_0, \dots)$.

Let $\chi^* = (x_t^*)_{t=0}^{\infty}$ be the optimal path of the initial problem $\max_{\chi \in \Phi(x_0)} U(\chi)$ with $\chi^* \neq (x_0, x_0, \dots)$. Then the following inequality is satisfied:

$$\inf_{t \geq 0} u(f(x_t^*) - x_{t+1}^*) < u(f(x_0) - x_0). \quad (5.1)$$

We observe that there are finitely many t such that $u(f(x_t^*) - x_{t+1}^*) < u(f(x_0) - x_0)$ (and, at least, one). Indeed, in the contrary case, with an infinite number of t satisfying this inequality, applying the part (3) of Lemma 2.1, we have $U(\chi^*) < u(f(x_0) - x_0)$ a contradiction.

Let T be the largest time index t such that $u(f(x_t^*) - x_{t+1}^*) < u(f(x_0) - x_0)$.

For any $t > T$, $u(f(x_t^*) - x_{t+1}^*) > u(f(x_0) - x_0)$. We observe that

$$\inf_{t > 0} u(f(x_{T+t}^*) - x_{T+t+1}^*) > u(f(x_0) - x_0).$$

⁹The reader interested in the dynamic properties of the optimal path under the RCK criterion, is referred to section 2.4.4 of chapter 2 in [19].

On the contrary, for any $\varepsilon > 0$, there are infinitely many t such that

$$u(f(x_t^*) - x_{t+1}^*) < u(f(x_0) - x_0) + \varepsilon.$$

By part (3) of Lemma 2.1, we obtain $U(\chi^*) < u(f(x_0) - x_0) / (1 - \delta)$, a contradiction.

Hence, $\inf_{t>0} u(f(x_{T+t}^*) - x_{T+t+1}^*) > u(f(x_0) - x_0)$, which implies the existence of $a > 0$ such that $u(f(x_t^*) - x_{t+1}^*) > u(f(x_0) - x_0) + a$ for any $t > T$.

Observe that $x_{T+1}^* \geq x_0$. Indeed, assume the contrary, $x_{T+1}^* < x_0$. Since $u(f(x_{T+1}^*) - x_{T+2}^*) > u(f(x_0) - x_0)$, this implies $x_{T+2}^* < x_0$. By induction, for every $t > 0$, $x_{T+t}^* < x_0$. By applying the part (3) of Lemma 2.1, we obtain $U(\chi^*) < u(f(x_0) - x_0)$, a contradiction.

Fix an $\varepsilon > 0$ sufficiently small such that

$$u(f(x_{T+1}^* - \varepsilon) - x_{T+2}^*) > u(f(x_0) - x_0) + a > u(f(x_T^*) - (x_{T+1}^* - \varepsilon)).$$

Denote by $\hat{\Pi}$ the subset of Π such that $\pi^{-1}(T) \leq T$ and $\pi^{-1}(T) < \pi^{-1}(T+1)$. Let us prove that

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) = \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*).$$

Indeed, take any $\pi \in \Pi$ which does not satisfy one of the two conditions in the definition of $\hat{\Pi}$, that is: (a) $\pi^{-1}(T) > T$ or (b) $\pi^{-1}(T) \geq \pi^{-1}(T+1)$.

(a) First, consider the case $\pi^{-1}(T) > T$. This means that the place T is now occupied by an element which was in a strictly higher place before the permutation. This implies the existence of some $\tilde{T} > T$ such that $\pi^{-1}(\tilde{T}) \leq T$ because T is finite. Recall that for every $t > T$, we have $f(x_t^*) - x_{t+1}^* > f(x_0) - x_0$. Hence $f(x_{\tilde{T}}^*) - x_{\tilde{T}+1}^* > f(x_0) - x_0$. Let $\hat{T} \equiv \min\{\tilde{T}\}$.

Let $T_1 \equiv \pi^{-1}(T)$ and $T_2 \equiv \pi^{-1}(\hat{T})$. Then, $\pi(T_1) = T$ and $\pi(T_2) = \hat{T}$. Consider an auxiliary permutation $\hat{\pi}$ such that $\hat{\pi}(t) = \pi(t)$ for any $t \neq T_1, T_2$, $\hat{\pi}(T_1) = \hat{T}$ and $\hat{\pi}(T_2) = T$. We have $\pi^{-1}(T) = T_1 = \hat{\pi}^{-1}(\hat{T})$ and, symmetrically, $\pi^{-1}(\hat{T}) = T_2 = \hat{\pi}^{-1}(T)$.

Let us show that $\hat{\pi} \in \hat{\Pi}$. Clearly, $\hat{\pi}^{-1}(T) = \pi^{-1}(\hat{T}) \leq T$.

Moreover, if $\hat{T} = T+1$, we have $\hat{\pi}^{-1}(T+1) = \hat{\pi}^{-1}(\hat{T}) = \pi^{-1}(T) > T \geq \pi^{-1}(\hat{T}) = \hat{\pi}^{-1}(T)$.

If $\hat{T} > T+1$, we have $\pi^{-1}(T+1) > T$, otherwise $T+1 < \hat{T}$ will be the smallest time index $\tilde{T} > T$ such that $\pi^{-1}(\tilde{T}) \leq T$, a contradiction. Then $\hat{\pi}^{-1}(T+1) = \pi^{-1}(T+1) > T \geq \pi^{-1}(\hat{T}) = \hat{\pi}^{-1}(T)$.

In this case, we obtain

$$\begin{aligned} & \sum_{t=0}^{\infty} \delta^t u(f(x_{\hat{\pi}(t)}^*) - x_{\hat{\pi}(t)+1}^*) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) \\ &= \delta^{\hat{\pi}^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) + \delta^{\hat{\pi}^{-1}(\hat{T})} u(f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*) \\ & - \delta^{\pi^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) - \delta^{\pi^{-1}(\hat{T})} u(f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*) \\ &= \delta^{\pi^{-1}(\hat{T})} u(f(x_T^*) - x_{T+1}^*) + \delta^{\pi^{-1}(T)} u(f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*) \\ & - \delta^{\pi^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) - \delta^{\pi^{-1}(\hat{T})} u(f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*) \\ &= \left[\delta^{\pi^{-1}(\hat{T})} - \delta^{\pi^{-1}(T)} \right] \left[u(f(x_T^*) - x_{T+1}^*) - u(f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*) \right] \\ &< 0, \end{aligned}$$

since $0 < \delta < 1$, $\pi^{-1}(\hat{T}) \leq T < \pi^{-1}(T)$ and $f(x_T^*) - x_{T+1}^* < f(x_{\hat{T}}^*) - x_{\hat{T}+1}^*$.

(b) $\pi^{-1}(T) \geq \pi^{-1}(T+1)$ is equivalent to $\pi^{-1}(T) > \pi^{-1}(T+1)$ because π^{-1} is a permutation and, then, $\pi^{-1}(T) \neq \pi^{-1}(T+1)$.

The case $\pi^{-1}(T) > \pi^{-1}(T+1)$ can be similarly treated.

Let $T_1 \equiv \pi^{-1}(T)$ and $T_2 \equiv \pi^{-1}(T+1)$. Consider an auxiliary permutation $\hat{\pi}$ such that $\hat{\pi}(t) = \pi(t)$ for any $t \neq T_1, T_2$, $\hat{\pi}(T_1) = T+1$ and $\hat{\pi}(T_2) = T$. We have $\pi^{-1}(T) = T_1 = \hat{\pi}^{-1}(T+1)$ and, symmetrically, $\pi^{-1}(T+1) = T_2 = \hat{\pi}^{-1}(T)$.

Let us show that $\hat{\pi} \in \hat{\Pi}$, that is $\hat{\pi}^{-1}(T) < \hat{\pi}^{-1}(T+1)$ and $\hat{\pi}^{-1}(T) \leq T$.

Clearly, $\hat{\pi}^{-1}(T) = \pi^{-1}(T+1) < \pi^{-1}(T) = \hat{\pi}^{-1}(T+1)$.

(b.1) If $\pi^{-1}(T) \leq T$, we have $\hat{\pi}^{-1}(T) = \pi^{-1}(T+1) < \pi^{-1}(T) \leq T$.

Thus, if $\pi^{-1}(T) \leq T$, we have that $\hat{\pi} \in \hat{\Pi}$. In this case, since

$$\begin{aligned} & \sum_{t=0}^{\infty} \delta^t u(f(x_{\hat{\pi}(t)}^*) - x_{\hat{\pi}(t+1)}^*) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t+1)}^*) \\ &= \delta^{\hat{\pi}^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) + \delta^{\hat{\pi}^{-1}(T+1)} u(f(x_{T+1}^*) - x_{T+2}^*) \\ & - \delta^{\pi^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) - \delta^{\pi^{-1}(T+1)} u(f(x_{T+1}^*) - x_{T+2}^*) \\ &= \delta^{\pi^{-1}(T+1)} u(f(x_T^*) - x_{T+1}^*) + \delta^{\pi^{-1}(T)} u(f(x_{T+1}^*) - x_{T+2}^*) \\ & - \delta^{\pi^{-1}(T)} u(f(x_T^*) - x_{T+1}^*) - \delta^{\pi^{-1}(T+1)} u(f(x_{T+1}^*) - x_{T+2}^*) \\ &= \left[\delta^{\pi^{-1}(T+1)} - \delta^{\pi^{-1}(T)} \right] \left[u(f(x_T^*) - x_{T+1}^*) - u(f(x_{T+1}^*) - x_{T+2}^*) \right] \\ &< 0. \end{aligned}$$

(b.2) If $\pi^{-1}(T) > T$, we recover the case (a).

Therefore, for any $\pi \notin \hat{\Pi}$, it is always possible to define an auxiliary permutation $\hat{\pi} \in \hat{\Pi}$ such that

$$\sum_{t=0}^{\infty} \delta^t u(f(x_{\hat{\pi}(t)}^*) - x_{\hat{\pi}(t+1)}^*) < \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t+1)}^*).$$

Hence

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t+1)}^*) = \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t+1)}^*).$$

Fix $\varepsilon > 0$ sufficiently small such that $0 < \varepsilon < x_{T+1}^*$, $0 < x_{T+2}^* < f(x_{T+1}^*) - \varepsilon$,

$$u(f(x_T^*) - (x_{T+1}^* - \varepsilon)) < u(f(x_0) - x_0),$$

and

$$u(f(x_0) - x_0) + a < u(f(x_{T+1}^* - \varepsilon) - x_{T+2}^*).$$

Consider the sequence $\hat{\chi} \in \Phi(x_0)$ such that $\hat{\chi}_t = x_t^*$ for any $t \neq T+1$ and $\hat{\chi}_{T+1} = x_{T+1}^* - \varepsilon$. We have $u(f(\hat{\chi}_T) - \hat{\chi}_{T+1}) < u(f(\hat{\chi}_{T+1}) - \hat{\chi}_{T+2})$.

The following equality is satisfied for $\varepsilon > 0$ sufficiently small:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(\hat{\chi}_{\pi(t)}) - \hat{\chi}_{\pi(t+1)}) = \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(\hat{\chi}_{\pi(t)}) - \hat{\chi}_{\pi(t+1)}).$$

Let $\varphi(x_{T+1}^*) \equiv u(f(x_T^*) - x_{T+1}^*)$ and $\psi(x_{T+1}^*) \equiv u(f(x_{T+1}^*) - x_{T+2}^*)$, where φ is strictly decreasing and strictly concave and ψ is strictly increasing and strictly concave. By the definition of derivative,

$$\begin{aligned}\varphi(x_{T+1}^* - \varepsilon) - \varphi(x_{T+1}^*) &= \varphi'(x_{T+1}^*)(-\varepsilon) - R_1(\varepsilon), \\ \psi(x_{T+1}^* - \varepsilon) - \psi(x_{T+1}^*) &= \psi'(x_{T+1}^*)(-\varepsilon) - R_2(\varepsilon),\end{aligned}$$

with $R_i(\varepsilon) > 0$ and $\lim_{\varepsilon \rightarrow 0} [R_i(\varepsilon)/\varepsilon] = 0$ for $i = 1, 2$. Then,

$$\begin{aligned}& u(f(x_T^*) - (x_{T+1}^* - \varepsilon)) - u(f(x_T^*) - x_{T+1}^*) \\ &= u'(f(x_T^*) - x_{T+1}^*) \varepsilon - R_1(\varepsilon) \\ & u(f(x_{T+1}^* - \varepsilon) - x_{T+2}^*) - u(f(x_{T+1}^*) - x_{T+2}^*) \\ &= u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*)(-\varepsilon) - R_2(\varepsilon).\end{aligned}$$

We obtain

$$\begin{aligned}& \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) \\ &= \delta^{\pi^{-1}(T)} [u(f(x_T^*) - (x_{T+1}^* - \varepsilon)) - u(f(x_T^*) - x_{T+1}^*)] \\ & \quad + \delta^{\pi^{-1}(T+1)} [u(f(x_{T+1}^* - \varepsilon) - x_{T+2}^*) - u(f(x_{T+1}^*) - x_{T+2}^*)] \\ &= \delta^{\pi^{-1}(T)} [u'(f(x_T^*) - x_{T+1}^*) \varepsilon - R_1(\varepsilon)] \\ & \quad + \delta^{\pi^{-1}(T+1)} [u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*)(-\varepsilon) - R_2(\varepsilon)] \\ &= \delta^{\pi^{-1}(T)} u'(f(x_T^*) - x_{T+1}^*) \varepsilon \\ & \quad - \delta^{\pi^{-1}(T+1)} u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*) \varepsilon - R(\varepsilon),\end{aligned}$$

with $R(\varepsilon) \equiv \delta^{\pi^{-1}(T)} R_1(\varepsilon) + \delta^{\pi^{-1}(T+1)} R_2(\varepsilon)$.

Recall that, for any $\pi \in \hat{\Pi}$, we have $\pi^{-1}(T+1) > \pi^{-1}(T)$, then $\pi^{-1}(T+1) \geq \pi^{-1}(T) + 1$ and

$$\begin{aligned}& \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) \\ &\geq \delta^{\pi^{-1}(T)} u'(f(x_T^*) - x_{T+1}^*) \varepsilon \\ & \quad - \delta^{\pi^{-1}(T)+1} u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*) \varepsilon - R(\varepsilon) \\ &= \varepsilon \delta^{\pi^{-1}(T)} [u'(f(x_T^*) - x_{T+1}^*) - \delta u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*)] - R(\varepsilon)\end{aligned}$$

By definition of T , we have

$$u(f(x_T^*) - x_{T+1}^*) < u(f(x_0) - x_0) < u(f(x_{T+1}^*) - x_{T+2}^*)$$

Since u is strictly increasing, we obtain $f(x_T^*) - x_{T+1}^* < f(x_{T+1}^*) - x_{T+2}^*$ and then

$$u'(f(x_T^*) - x_{T+1}^*) > u'(f(x_{T+1}^*) - x_{T+2}^*).$$

Therefore,

$$\begin{aligned}
& \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) \\
& \geq \varepsilon \left(\delta^{\pi^{-1}(T)} [u'(f(x_T^*) - x_{T+1}^*) - \delta u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*)] - \frac{R(\varepsilon)}{\varepsilon} \right) \\
& \geq \varepsilon \left(\delta^T [u'(f(x_T^*) - x_{T+1}^*) - \delta u'(f(x_{T+1}^*) - x_{T+2}^*) f'(x_{T+1}^*)] - \frac{R(\varepsilon)}{\varepsilon} \right).
\end{aligned}$$

Since $x_{T+1}^* \geq x_0$ and $u'(f(x_T^*) - x_{T+1}^*) > u'(f(x_{T+1}^*) - x_{T+2}^*)$, we have

$$\begin{aligned}
& \frac{1}{\varepsilon} \left[\sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) - \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) \right] \\
& \geq \delta^T u'(f(x_T^*) - x_{T+1}^*) [1 - \delta f'(x_0)] - \frac{R(\varepsilon)}{\varepsilon}.
\end{aligned}$$

Let ε converge to zero, the RHS converges to a strictly positive value because $\delta f'(x_0) < \delta f'(x^*) = 1$. Moreover, for $\varepsilon > 0$ sufficiently small, the right-hand side is strictly superior to $\delta^T u'(f(x_T^*) - x_{T+1}^*) [1 - \delta f'(x_0)] / 2$.

Hence, if ε is sufficiently small, we obtain

$$\begin{aligned}
& \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) \\
& > \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) + \frac{1}{2} \varepsilon \delta^T u'(f(x_T^*) - x_{T+1}^*) [1 - \delta f'(x_0)].
\end{aligned}$$

We observe that ε is independent on $\pi \in \hat{\Pi}$. Thus, we have

$$\begin{aligned}
& \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) \\
& = \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(\hat{x}_{\pi(t)}) - \hat{x}_{\pi(t)+1}) \\
& \geq \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) + \frac{1}{2} \varepsilon \delta^T u'(f(x_T^*) - x_{T+1}^*) [1 - \delta f'(x_0)] \\
& > \inf_{\pi \in \hat{\Pi}} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*) = \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}^*) - x_{\pi(t)+1}^*),
\end{aligned}$$

a contradiction. Hence, the unique optimal path is $\chi = (x_0, x_0, \dots)$ and

$$\max_{\chi \in \Phi(x_0)} \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}) - x_{\pi(t)+1}) = \frac{u(f(x_0) - x_0)}{1 - \delta}.$$

(3) According to (2.2), for any t , $\inf_{s \geq 0} u(f(x_{t+s}) - x_{t+s+1}) \leq u(f(\bar{x}) - \bar{x})$.¹⁰ Hence, for any $\varepsilon > 0$, there exists a subsequence $(t_n)_{n=0}^{\infty}$ such that

$$u(f(x_{t_n}) - x_{t_n+1}) \leq u(f(\bar{x}) - \bar{x}) + \varepsilon.$$

¹⁰ See part (ii) of Proposition A.2 in [15].

Applying the part (2) of Lemma 2.1, we obtain

$$U(\chi) \leq \frac{u(f(\bar{x}) - \bar{x})}{1 - \delta} \quad (5.2)$$

for every $\chi \in \phi(x_0)$.

In the proof of part (ii) of Proposition A.2, [15] show that there are infinitely many optimal paths $\chi = (x_0, x_1, \dots)$ such that

$$\inf_{t \geq 0} u(f(x_t) - x_{t+1}) = u(f(\bar{x}) - \bar{x}).$$

Let χ be one of this paths. We have

$$\begin{aligned} U(\chi) &\equiv \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} \delta^t u(f(x_{\pi(t)}) - x_{\pi(t)+1}) \geq \sum_{t=0}^{\infty} \delta^t \inf_{t \geq 0} u(f(x_t) - x_{t+1}) \\ &\geq \sum_{t=0}^{\infty} \delta^t u(f(\bar{x}) - \bar{x}) = \frac{u(f(\bar{x}) - \bar{x})}{1 - \delta}. \end{aligned}$$

According to (5.2), we obtain $U(\chi) = u(f(\bar{x}) - \bar{x}) / (1 - \delta)$. Thus, every optimal path are decreasing and converges to \bar{x} .

Proof of Proposition 3.1

To simplify the presentation, RZA will denote the weighted sum of RCK and the third Rawlsian criterion introduced by [27].

(1) Focus on the case $0 < x_0 \leq x^*$. Let $(x_t^*)_{t=0}^{\infty}$ be the optimal path under the RCK criterion. This sequence is increasing and converges to the *modified golden rule* x^* , solution to $\delta f'(x) = 1$ (Proposition 2.4.4 in [19]).

Moreover, the corresponding consumption sequence $c_t^* = f(x_t^*) - x_{t+1}^*$ is increasing and converges to $c^* = f(x^*) - x^*$ (see the Euler equation in Proposition 2.4.4 in [19]). This implies:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}^*) = \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*).$$

Hence, for every feasible sequence $(x_t)_{t=0}^{\infty}$ with the corresponding consumption sequence $c_t = f(x_t) - x_{t+1}$, we have

$$\begin{aligned} &(1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}^*) \\ &= (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*) + \lambda \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*) \\ &\geq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) \\ &\geq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}). \end{aligned}$$

Therefore, the optimal path under the RCK criterion is also the optimal path under the RZA one.

(2) Now, consider the nontrivial case: $x_0 > x^*$. We will prove that the optimal path coincides with the one in [15].

Let $(x_t)_{t=0}^{\infty}$ be the optimal path under RZA criterion, and $c_t = f(x_t) - x_{t+1}$. First, we will prove that $x_t > x^*$ for any $t \geq 0$.

Assume the contrary, that is the existence of T such that $x_T \leq x^*$. It is known that there exists some $t \geq T$ such that $c_t \leq f(x_T) - x_T \leq f(x^*) - x^* = c^*$. Moreover, there are only finitely many t such that $c_t < c^* = f(x^*) - x^*$. Indeed, by part (2) of Lemma 2.1, the existence of infinitely many t such that $c_t < c^*$ implies

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) \leq u(c^*).$$

Recall that $(x_t^*)_{t=0}^{\infty}$ is the optimal capital path under the RCK criterion. Moreover, since $x_0 > x^*$ (see Proposition 2.4.4 in [19]), the corresponding consumption sequence $(c_t^*)_{t=0}^{\infty}$ is decreasing and converges to c^* . We obtain:

$$\begin{aligned} & (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}^*) \\ & \geq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t^*) + \lambda u(c^*) \\ & > (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}), \end{aligned}$$

a contradiction with the hypothesis that $(x_t)_{t=0}^{\infty}$ is the optimal path under the RZA criterion.

We have proven that there is a finite number of t such that $c_t < c^*$. Let T be the biggest period satisfying this inequality. Therefore, $x_{T+1} \geq x^*$. Indeed, if $x_{T+1} < x^*$, following the same argument we used to solve the optimization problem under the Rawls criterion (see inequality (5.1)), we obtain:

$$\inf_{t > 0} u(f(x_{T+t}) - x_{T+t+1}) < u(c^*).$$

This implies the existence of $t > 0$ such that $c_{T+t} < c^*$, a contradiction with the definition of T .

Fix any ε such that $0 < \varepsilon < x_{T+1}$ and $0 < x_{T+2} < f(x_{T+1}) - \varepsilon$. Define the capital sequence $(\hat{x}_t)_{t=0}^{\infty}$ such that $\hat{x}_t = x_t$ for any $t \neq T + 1$ and $\hat{x}_{T+1} = x_{T+1} - \varepsilon$. Hence,

$$\begin{aligned} & \sum_{t=0}^{\infty} \delta^t u(\hat{c}_t) - \sum_{t=0}^{\infty} \delta^t u(c_t) \\ & = \delta^T u(\hat{c}_T) + \delta^{T+1} u(\hat{c}_{T+1}) - \delta^T u(c_T) - \delta^{T+1} u(c_{T+1}) \\ & \geq \delta^T u'(\hat{c}_T) (\hat{c}_T - c_T) + \delta^{T+1} u'(\hat{c}_{T+1}) (\hat{c}_{T+1} - c_{T+1}) \\ & = \delta^T u'(\hat{c}_T) (f(x_T) - (x_{T+1} - \varepsilon) - [f(x_T) - x_{T+1}]) \\ & \quad + \delta^{T+1} u'(\hat{c}_{T+1}) [f(x_{T+1} - \varepsilon) - x_{T+2} - f(x_{T+1}) + x_{T+2}] \\ & \geq \delta^T u'(\hat{c}_T) \varepsilon - \delta^{T+1} u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon) \varepsilon \\ & = \varepsilon \delta^T [u'(\hat{c}_T) - \delta u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon)], \end{aligned} \tag{5.3}$$

because of the concavity of f and u . We obtain:

$$\frac{1}{\varepsilon \delta^T} \left[\sum_{t=0}^{\infty} \delta^t u(\hat{c}_t) - \sum_{t=0}^{\infty} \delta^t u(c_t) \right] \geq u'(\hat{c}_T) - \delta u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon).$$

Since $u'(c_T) > u'(c_{T+1})$ and $\delta f'(x_{T+1}) \leq \delta f'(x^*) = 1$, for ε small enough, the RHS is strictly positive and, thus,

$$\lim_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon} \left[\sum_{t=0}^{\infty} \delta^t u(\hat{c}_t) - \sum_{t=0}^{\infty} \delta^t u(c_t) \right] > 0.$$

Then, for ε sufficiently small, $\sum_{t=0}^{\infty} \delta^t u(\hat{c}_t) > \sum_{t=0}^{\infty} \delta^t u(c_t)$.

Let Π_T be the set of permutations π such that $\pi^{-1}(T) < \pi^{-1}(T+1)$. Since $c_T < c^* \leq c_{T+1}$, we obtain:

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}) = \inf_{\pi \in \Pi_T} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}).$$

Now, fix any permutation $\pi \in \Pi^T$ with $\pi^{-1}(T) < \pi^{-1}(T+1)$. Applying similar arguments as in (5.3), we obtain:

$$\begin{aligned} & \sum_{t=0}^{\infty} (1-\delta) \delta^t u(\hat{c}_{\pi(t)}) - \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}) \\ &= \delta^{\pi^{-1}(T)} u(\hat{c}_T) + \delta^{\pi^{-1}(T+1)} u(\hat{c}_{T+1}) - \delta^{\pi^{-1}(T)} u(c_T) - \delta^{\pi^{-1}(T+1)} u(c_{T+1}) \\ &= \delta^{\pi^{-1}(T)} \left([u(\hat{c}_T) - u(c_T)] + \delta^{\pi^{-1}(T+1) - \pi^{-1}(T)} [u(\hat{c}_{T+1}) - u(c_{T+1})] \right) \\ &\geq \varepsilon \delta^{\pi^{-1}(T)} \left[u'(\hat{c}_T) - \delta^{\pi^{-1}(T+1) - \pi^{-1}(T)} u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon) \right] \\ &\geq \varepsilon \delta^{\pi^{-1}(T)} \left[u'(\hat{c}_T) - \delta u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon) \right], \end{aligned}$$

with $\hat{x}_{T+1} = x_{T+1} - \varepsilon$.

Therefore, for any $\pi \in \Pi_T$,

$$\begin{aligned} & \sum_{t=0}^{\infty} (1-\delta) \delta^t u(\hat{c}_{\pi(t)}) \\ &\geq \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}) + \varepsilon \delta^{\pi^{-1}(T)} \left[u'(\hat{c}_T) - \delta u'(\hat{c}_{T+1}) f'(x_{T+1} - \varepsilon) \right] \\ &\geq \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}), \end{aligned}$$

for ε small enough. Then, for ε small enough, for any $\pi \in \Pi_T$,

$$\begin{aligned} \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(\hat{c}_{\pi(t)}) &= \inf_{\pi \in \Pi_T} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(\hat{c}_{\pi(t)}) \\ &\geq \inf_{\pi \in \Pi_T} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}) \\ &\geq \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1-\delta) \delta^t u(c_{\pi(t)}). \end{aligned}$$

Therefore, for $\varepsilon > 0$ sufficiently small, we have

$$\begin{aligned} & (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(\hat{c}_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(\hat{c}_{\pi(t)}) \\ & > (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}), \end{aligned}$$

a contradiction.

This contradiction comes from the hypothesis that there exists t such that $x_t \leq x^*$. Hence $x_t > x^*$ for any $t \geq 0$.

Let us prove that $c_t \geq c_{t+1}$ for any $t \geq 0$. Assume the existence of some T such that $c_T < c_{T+1}$. Fix $\varepsilon > 0$ such that $0 < \varepsilon < x_{T+1}$ and $f(x_T) - x_{T+1} + \varepsilon < f(x_{T+1} - \varepsilon) - x_{T+2}$. Consider the sequence $(\hat{x}_t)_{t=0}^{\infty}$ as in the first part of point (2) of the current proof. Using the same arguments and considering that $x_{T+1} > x^*$ implies $\delta f'(x_{T+1}) < 1$, we can prove that the sequence $(x_t)_{t=0}^{\infty}$ is not optimal, a contradiction.

This contradiction comes from the hypothesis there exists T such that $c_T < c_{T+1}$. Hence, the sequence $(c_t)_{t=0}^{\infty}$ is non-increasing: $c_t \geq c_{t+1}$ for any $t \geq 0$. Since the utility function u is strictly increasing, we have $\lim_{t \rightarrow \infty} u(c_t) = \inf_{t \geq 0} u(c_t)$.

Hence, for every $\varepsilon > 0$, there exists an infinite number t such that $u(c_t) < \inf_{t \geq 0} u(c_t) + \varepsilon$. Applying part (2) of Lemma 2.1, we obtain $\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) \leq \inf_{t \geq 0} u(c_t)$. Clearly,

$$\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) \geq \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t \inf_{t \geq 0} u(c_t) = \inf_{t \geq 0} u(c_t).$$

Thus $\inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) = \inf_{t \geq 0} u(c_t)$.

Hence, we have

$$\begin{aligned} & (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) \\ & = (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{t \geq 0} u(c_t). \end{aligned}$$

Consider the sequence $(\bar{x}_t)_{t=0}^{\infty}$ which is the optimal path under the hybrid criterion presented in section 2 of [15], and the corresponding consumption sequence $(\bar{c}_t)_{t=0}^{\infty}$. We have

$$\begin{aligned} & (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}) \\ & = (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{t \geq 0} u(c_t) \\ & \leq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(\bar{c}_t) + \lambda \inf_{t \geq 0} u(\bar{c}_t) \\ & \leq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(\bar{c}_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(\bar{c}_{\pi(t)}) \\ & \leq (1 - \lambda) \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_t) + \lambda \inf_{\pi \in \Pi} \sum_{t=0}^{\infty} (1 - \delta) \delta^t u(c_{\pi(t)}). \end{aligned}$$

Hence, all these inequalities hold with equality and, finally, the two sequences $(x_t)_{t=0}^{\infty}$ and $(\bar{x}_t)_{t=0}^{\infty}$ coincide.

In [15], the authors proved that the optimal path under the criterion that is the weighted sum of RCK and the first Rawlsian is non-increasing when $x_0 \geq x^*$. Therefore, this path coincides with the optimal path under the mixed criterion presented in [15], with $a = \lambda / (1 - \lambda)$.

For $x_0 \geq x^*$, in [15], the optimal path can be described as follows:

(2.1) If $0 \leq a \leq a_1$, the equality part plays no role and the optimal path **coincides the optimal** path of the RCK criterion.

(2.2) When $a_1 < a < a_2$, the economy converges to the *modified golden rule* as in the RCK model, but with a larger discount factor $\tilde{\delta} > \delta$.

(2.3) If $a \geq a_2$, the equality part fully dominates and we recover the optimal path of the first Rawlsian criterion.

Let $\lambda_1 \equiv a_1 / (1 + a_1)$ and $\lambda_2 \equiv a_2 / (1 + a_2)$, we have $0 \leq \lambda_1 \leq \lambda_2 \leq 1$ with $a_2 > 0$. Moreover, $\lambda \leq \lambda_1$ if and only if $a \leq a_1$ and $\lambda \geq \lambda_2$ if and only if $a \geq a_2$. Hence, we obtain the results using Proposition 2.2 in [15].

Acknowledgments

The authors acknowledge the financial support of the LABEX MME-DII (ANR-11-LBX-0023-01).

REFERENCES

- [1] F. Alvarez-Cuadrado, N.V. Long, A mixed Bentham - Rawls criterion for intergenerational equity: Theory and implications, *Journal of Environmental Economics and Management* 58 (2009) 154-168.
- [2] K. Arrow, *Essays in the Theory of Risk-Bearing*, North-Holland, 1970.
- [3] K.J. Arrow, Rawls' principle of just savings, *The Swedish Journal of Economics*, 75 (1973) 323-335.
- [4] G.B. Asheim, I. Ekeland, Resource conservation across generations in a Ramsey - Chichilnisky model, *Economic Theory* 61 (2016) 611-639.
- [5] A. Ayong Le Kama, T. Ha-Huy, C. Le Van, K. Schubert, A never-decisive and anonymous criterion for optimal growth models, *Economic Theory* 55 (2014) 281-306.
- [6] K. Basu, T. Mitra, Aggregating infinite utility streams with intergenerational equity: The impossibility of being Paretian, *Econometrica* 71 (2003) 1557-1563.
- [7] G.A. Calvo, Optimal maximin accumulation with uncertain future technology, *Econometrica* 45 (1977) 317-327.
- [8] C. Chambers, F. Echenique, On multiple discount rates, *Econometrica* 86 (2018) 1325-1346.
- [9] G. Chichilnisky, An axiomatic approach to sustainable development, *Social Choice and Welfare* 13 (1996) 231-257.
- [10] G. Chichilnisky, What is sustainable development? *Land Economics* 73 (1973) 467-491.
- [11] P. Diamond, The evaluation of infinite utility streams, *Econometrica* 33 (1965) 170-177.
- [12] C. Figuères, M. Tidball, Sustainable exploitation of a natural resource: A satisfying use of Chichilnisky's criterion, *Economic Theory* 49 (2012) 243-265.
- [13] D. Gale, On optimal development in a multi-sector economy, *Review of Economic Studies*, 34 (1967) 1-18.
- [14] T. Ha-Huy, A tale of two Rawlsian criteria, *Mathematical Social Sciences*, 118 (2022) 30-35.
- [15] T. Ha-Huy, T.T.M. Nguyen, Saving and dissaving under Ramsey-Rawls criterion, *Journal of Mathematical Economics* 103 (2022) **103018**.
- [16] G. Heal, *Valuing the Future*, Economic Theory and Sustainability, Columbia University Press, 1998.
- [17] T.J. Koopmans, Stationary ordinal utility and impatience, *Econometrica* 28 (1960) 287-309.
- [18] T.J. Koopmans, Representation of preference orderings over time, In: C. McGuire, R. Radner (eds.), *Decision and Organisation*, North-Holland, 1972.

- [19] C. Le Van, R.-A. Dana, *Dynamic Programming in Economics*, Kluwer, 2002.
- [20] C. Le Van, L. Morhaim, Optimal growth models with bounded or unbounded returns: A unifying approach, *Journal of Economic Theory* 105 (2002) 157-187.
- [21] J.A. Mirlees, Optimum growth when technology is changing, *Review of Economic Studies* 34 (1967) 95-124.
- [22] E. Phelps, *Golden Rules of Economic Growth*, Norton, 1966.
- [23] E.S. Phelps, J.G. Riley, Rawlsian growth: Dynamic programming of capital and wealth for intergeneration "maximin" justice, *Review of Economic Studies*, 45 (1978) 103-120.
- [24] F.P. Ramsey, A mathematical theory of saving, *Economic Journal*, 38 (1928) 543-559.
- [25] J. Rawls, *A Theory of Justice*, Clarendon, 1971.
- [26] N.L. Stokey, R.E. Lucas, *Recursive Methods in Economic Dynamics*, Harvard University Press, 1989.
- [27] S. Zuber, G.B. Asheim, Justifying social discounting: The rank-discounted utilitarian approach, *Journal of Economic Theory* 147 (2012) 1572-1601.